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Auditory Perception in Open Field: Distance Estimation

by Kim F. Fluitt, Timothy Mermagen, and Tomasz Letowski

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14. ABSTRACT

The purpose of this study was to expand our knowledge about auditory distance estimation at larger distances in an open-field environment in which auditory sensations are affected by meteorological factors, such as wind, temperature, and humidity. Of particular concern are the conditions where visual distance estimation is compromised, and auditory distance estimation has important military implications and contributes to Soldier safety and mission effectiveness. Our goal was accomplished by collecting both acoustic (target sound and noise levels) and meteorological (wind direction and strength, temperature, atmospheric pressure, and humidity) data for each experimental trial. Twenty-four subjects (men and women, ages 18–25) participated in this study. Seven types of sounds together with blank (no sound) trials were presented to the listeners. The sounds were delivered from six loudspeakers located 25, 50, 100, 200, 400, and 800 m from the listener. The actual loudspeakers were spread across the field together with 12 additional dummy loudspeaker boxes providing visual uncertainty regarding the sound source location. The results of the study indicate that auditory distance judgments in the open field at 25-m distance and beyond underestimate the actual distances to sound sources regardless of the distance.

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Executive Summary

This report summarizes the state-of-the-art knowledge about the mechanism of auditory distance perception and reports the results of the distance estimation study conducted in an open field for distances in the 25- to 800-m range. Since this study seems to be the first study of this kind, it poses more questions than it provides definite answers. A range of listeners' behaviors has been identified, but caution is advised in generalizing the reported data due to the exploratory nature of this study and the relatively limited number of samples of both listening conditions and the participants. In addition, interdependence of temperature, humidity, and environmental noise make some observations tentative and in need of more rigorous confirmation.

In summary, within the constraints of the reported study, the following conclusions can be made:

- Auditory distance estimation judgments in the open field differ greatly among the listeners; however, for most listeners the perceived distance and the physical distance are monotonically related.
- The results of the study indicate that auditory distance judgments in the open field at a 25-m distance and beyond underestimate the actual distances to sound sources regardless of the distance.
- Some of the listeners participating in the study generally overestimated all distances to the sound sources; this behavior can be explained by either the expectations caused by a large visible space or by lack of internal concept of a distance resulting in the same numeric estimate across a range of distances.
- The type of sound source had an effect on the distance judgments; however, some of the observed environmental effects were not always clear.
- The effects of temperature, humidity, and environmental noise are interrelated and difficult to separate analytically; however, both increased humidity and lower temperature increased distance underestimation in the current study.
- Increased level of environmental noise at lower temperatures affected the audibility of projected sounds but did not seem to clearly affect distance estimation judgments.
- Downward wind increased the degree of distance underestimation across all sound sources and distances (upward wind has not been studied).
- Listeners' responses did not reveal any specific distance that they associated with the location of a particular sound source.

We hope that the results of this study will increase the listeners' awareness of the complex influences affecting listeners' behaviors in open field under changing weather conditions. However, further studies are needed to expand our knowledge about the nature of auditory distance estimations made under such environmental conditions and to confirm or correct reported findings.

1. Introduction

Auditory spatial perception is the ability to perceive relative locations of sound sources in the environment and the spatial character of the surrounding acoustic space. Any property of an auditory event causing a rise to a spatial sensation is called a spatial cue. Specific types of judgments resulting from spatial cues are categorized and discussed in the psychoacoustic literature as horizontal localization, vertical localization, auditory distance estimation, and spaciousness assessment. While judgments of directions toward sound sources received considerable interest in psychoacoustic literature, the judgments of auditory distance, and especially the judgments of spaciousness, received much less attention. The most likely reason for literature's special focus on the directional positions of sound sources is the criticality of directional information for human well-being. Hearing a sound source in a specific direction is important for human safety, spatial orientation, and auditory awareness of the environment, and it helps in effective speech communication.

Additional factors contributing to this focus are the relative independence of directional recognition of the acoustic characteristics of sound sources, of the complexity of surrounding environments, of the listener's hearing sensitivity, and of the listener's familiarity with the sound sources. However, all these factors greatly affect auditory judgments of distance and of the spaciousness of the surrounding environment, making them much harder to quantify for a population (Schaffer, 1977). In addition, some of the distance and spaciousness estimation cues can be ambiguous (e.g., sound intensity, sound spectrum) or are fairly weak (e.g., binaural cues, background noise). As a result, the judgments of distance and acoustic space are more complex, have higher cognitive load, and are more variable than the judgments of direction, and their results are much more difficult to model and generalize (e.g., Blauert, 2001).

Human horizontal and vertical localization judgments[*] and formal and methodological issues related to directional localization[†] of sound sources have been recently reviewed by Letowski and Letowski (2012). Comprehensive summaries of the issues related to auditory distance estimation have been published by several authors, including Coleman (1963), Blauert (2001), and Zahorik et al. (2005). However, these summaries were based on auditory research conducted primarily in closed spaces and at relatively short distances up to about 25 m. Very few studies were reported to be conducted in an open space, and those reported did not involve distances exceeding 50 m.

[*] In some studies oblique compound judgments, which are the judgments of direction involving both vertical and horizontal direction components, were also used.

[†] In some publications the term "localization" is used to describe both directional and distance estimation judgments, while in others its use is restricted to directional localization. The restricted meaning of this term was used by Letowski and Letowski (2012).

The first part of this technical report provides a comprehensive review of concepts related to auditory distance judgments. It also includes an overview of environmental conditions that affect sound propagation in both closed and open spaces. The second part provides new numerical distance estimation data for free-field sound sources located at distances from 25 to 800 m and uses these data as a basis for a discussion of the physical and psychological variables affecting auditory distance estimation in an open space. The topic of echolocation (judging the distance to a silent physical object by emitting a sound and listening to its reflection from the object) is beyond the scope of this report, but interested readers may find a comprehensive treatment of this subject in Griffin (1959) and Kish (1995) regarding humans and in Howard (2012) regarding birds and animals.

2. Distance Perception

Distance perception, sometimes referred to as ranging (Howard, 2012), is the human ability to determine the distance between oneself and a target in space or the distance between two targets in space. The distance to a target can be judged on the basis of its visual, olfactory, and/or auditory properties. Distance judgments may have a form of distance discrimination or distance estimation. Distance discrimination is a relative judgment of the distance in terms of farther-closer, less-more, or same-different. Distance discrimination threshold is calculated as a fraction (percentage) of the distance change that is noticeable by the observer. Distance estimation is an absolute judgment about distance in terms of meters, feet, or time to travel; categorical judgment of distance in terms of near-far or predetermined categories; or a direct-action estimation of distance by reaching for the target or walking toward the target. The first two classes of judgments are *explicit estimations*, while the third one is an *implicit estimation* (e.g., Servos, 2000). Perceived and physical distance seem to be monotonically related but can be quite different. In general, human estimation of distance is much less accurate than the determination of angular direction, and observers normally underestimate the magnitude of actual distances.

There are three basic dichotomies that can be used in classifying distance judgments. The first dichotomy divides distance judgments into static (explicit, no-action) and dynamic (implicit, directed-action) behaviors of the judges (observers, listeners). In static (no-action) estimation, the judge estimates the distance to a given target from his/her stationary location. These estimates are usually numerical but also can be comparative in relation to other objects in space. In implicit (directed-action) estimation, the observer reaches for (e.g., infants) or walks toward (e.g., blindfolded) a target.

The second dichotomy refers to static (stationary) and dynamic (moving) behaviors of the targets. Although dynamic behaviors of both judges and targets are discussed in the theoretical part of this report, the main focus of the report is on the human ability to assess the distance numerically from a stationary position (explicit estimation). In an open space and for long distances, the directed-action (implicit) estimation is often impractical and in many cases unrealistic.

The third dichotomy divides distance judgments into egocentric judgments and exocentric judgments (Klatzky, 1998). Egocentric judgments, or body-centered judgments, are the judgments where the point of reference is the observer's location in space. The specific subjective reference point that people use for visual egocentric judgments is the point that lies between the eyes of the observer. In the case of auditory judgments, it is the midpoint of the interaural axis of the listener* (e.g., Funaishi, 1926; Komoda and Ono, 1974; Mitson et al., 1976; Neelon et al., 2004). The estimation that the target is located at a certain distance from the observer is an egocentric judgment. In the case of auditory judgments, the sound source can be perceived as located either in the head of the listener (such situation takes place in most earphone listening) or outside of the head. In the latter case, the sound source can be in front of, behind, to the left, to the right, above, or below the listener. Exocentric judgments, also called allocentric or geocentric judgments, are based on the external frame of reference and are independent of the actual location of the observer. The location of one target in space is referenced to the location of another target (e.g., a landmark) or to the axes of the external frame of reference. Giving the response as *farther north of the tree* is an exocentric judgment, rather than *farther to my right*.

In general, egocentric judgments are more accurate than exocentric judgments (e.g., Indow, 2004; Sedgwick, 1986). For example, Loomis et al. (1992), Philbeck et al. (2004), Rieser et al. (1990), and others reported that blindfolded observers could walk with high accuracy toward the previously sighted target for distances as great as 22 m. In contrast, visual exocentric distances are typically largely overestimated by observers when required to reproduce the extent of the distance by walking in other directions (e.g., Kudoh, 2005; Loomis et al., 1992; Philbeck et al., 2004; Wartenberg and Wiborg, 2003). The degree of overestimation seems to be proportional to the size of the visual angle subtended between the egocentric lines to both ends of the exocentric distance (Levin and Haber, 1993; Matsushima et al., 2005). Similarly, auditory egocentric judgments were reported more accurate than auditory exocentric judgments (e.g., Pavlovic et al., 2009).

Exocentric judgments, e.g., judgments of distances in a front-to-parallel plane and judgments of distances along axes not passing through the observer, need to be differentiated from the depth judgments—that is, judgments of distance between two targets aligned linearly along the egocentric axis. Although the latter judgments can be technically referred to as exocentric judgments, they are in fact differential egocentric judgments. Accuracy of these judgments is dependent on the human ability to perceive the differences in egocentric distances and, more

*According to Cox (1999) and Neelon et al. (2004), the auditory egocenter is located behind (posteriorly to) the interaural axis (approximately 12 cm behind the visual egocenter and 7 cm behind the interaural axis), suggesting the existence of a large audiovisual parallax effect.

generally, the ability to perceive the extent of the surrounding space in a given direction. These judgments will be further referred to as *depth judgments* to differentiate them from direct *distance judgments*. Depth judgments, as well as all other comparative distance judgments, can be made when the two judged objects are available simultaneously or in succession. In general, as the average distance from the listener to the sound sources increases, the perception of depth between the two sound sources decreases, and ultimately, it becomes impossible to discriminate between the locations of the two sound sources.

3. Auditory Distance Estimation

Auditory distance estimation is an estimation of a distance to a sound source on the basis of perceived sound. Estimated distance is the perceptual measure of a physical distance. The goal of auditory distance estimation is to determine the perceived location of a real or phantom sound source generating a specific auditory event. Such judgments can be made in real surrounding space in respect to natural and electroacoustic sound sources or in virtual reality space. The differentiation between real and phantom sound sources is important in the case of electroacoustic sound sources, which in most cases simulate specific environments rather than emit (reproduce) the natural image of a specific natural sound source. In the former case, the accuracy of judgment is the difference between the perceived and intended location of the sound source. In the latter case, it is the difference between the perceived and physical location of a sound source. Since both types of judgments are equally important, further references to physical location of the sound source will mean physical or intended simulated location.

The result of an estimation of auditory distance is dependent on the availability of several auditory distance cues, such as sound intensity, sound spectrum, and audibility of sound reflections from surrounding objects. These cues are described together with other potential cues in section 4. In most cases, the dominant distance cue is sound intensity. Distance estimation accuracy seems to be independent of the shape of the listener's head-related transfer function (HRTF) (Zahorik, 2002b). This may indicate that the listener's abilities to make accurate distance and direction judgments are fairly independent.

Perceived distance is a prothetic (ratio scale) perceptual phenomenon (continuum) (Stevens, 1957; Stevens and Guirao, 1962). It has a natural zero point (egocenter point) and a unit of measurement (e.g., meter). Each prothetic continuum (y) is exponentially related to the underlying physical dimension (x) by a psychophysical power law $y = kx^n$ (see Stevens' power law [Stevens, 1955; 1957; Stevens and Galanter, 1957]):

$$PD = kd^a, \tag{1}$$

where *PD* is the perceived distance, *d* is the physical distance, α is the sensitivity of the observer to perceived distance, and *k* is an arbitrary constant dependent on the unit of estimation. If $\alpha = 1$, then the physical or intended distance to the target is accurately perceived (Da Silva, 1985; Weist and Bell, 1985). Values $\alpha < 1$ indicate distance underestimation and values $\alpha > 1$ indicate distance overestimation.

Our perceptual world is generally visually oriented. Most perceptual phenomena were initially studied for vision and are best understood for the sense of vision. Therefore, a discussion of auditory distance perception may benefit from a brief explanation of visual distance perception. In the case of vision, egocentric visual distance estimates obtained in experimental studies are nearly linearly related to physical distances for short distances up to 15–20 m (e.g., Fukusima et al., 1997; Gibson and Bergman, 1954; Gibson et al., 1955; Loomis et al., 1992; 1996; Rand et al., 2011; Sedgwick, 1986). At larger distances, the observers begin to underestimate the physical distance, and the degree of underestimation increases as the viewing distance increases approaching an asymptotic ceiling (Gogel, 1993; Loomis and Philbeck, 1999). Sedgwick (1986) conducted an extensive review of visual distance estimation data and reported that the values of exponent α (equation 1) fitting the data varied quite extensively from 0.38 to 1.20 depending on the experimental conditions and observers. Aznar-Casanova et al. (2006) conducted a similar comparative study and concluded that large values of exponent α ($\alpha > 1$) were usually reported for short distances (d < 1 m; personal space), close to unity values ($\alpha = 1$) for medium distances (1 m < d < 20 m; action space), and small exponent values ($\alpha < 1$) for long distances (d > 20 m). In addition, it seems that observers underestimate visual distances to targets to a greater degree in open than in closed spaces (e.g., Aznar-Casanova et al., 2006; Teghtsoonian and Teghtsoonian, 1969; 1970).

In the case of audition, the same general relationship as discussed for vision exists, but the degree of distance underestimation is greater and the distance estimation ceiling is achieved earlier (Mershon and King, 1975; Nielsen, 1993). This ceiling has been called *auditory horizon*[*] by Békésy (1949) and is analogous to the visual horizon (Sedgwick, 1983; Proffitt, 2006). The distance to the horizon depends on the listener, available auditory cues, and the acoustic environment, thus it can vary from one situation to another. Zahorik (2002a) compared results of 10 studies (33 data sets) and reported that the average exponent of the exponential function as $\alpha = 0.59$ (SD = 0.24) and the constant of proportionality as k = 1.66 (SD = 0.92). The exponents fitted to individual data ranged from 0.15 to 0.7 and varied much larger between the listeners than between the test conditions (environments). His own study conducted in virtual space (distances from 0.3 to 14.0 m) resulted in $\alpha = 0.39$ (SD = 0.13) and k = 1.32 (SD = 0.56). In a later study, Zahorik et al. (2005) expanded the analysis conducted by Zahorik (2002a) on results of 21 studies (84 data sets) and reported that average exponent as $\alpha = 0.54$ and the constant of proportionality as k = 1.3.

[*] Auditory horizon is the perceptual representation of acoustic horizon, which is the farthest distance in a given direction from which a given sound can be heard.

Several studies performed in both real and simulated (headphones) environments[*] indicated that at short physical distances, the perceived distance increases almost linearly with the physical distance (Békésy, 1949; Bronkhorst and Houtgast, 1999) or the listeners slightly overestimate its value (Ashmead et al., 1995; Brungart and Scott, 2001; Kerber et al., 2004; Kopčo and Shinn-Cunningham, 2011; Loomis et al., 1996, 1998; Speigle and Loomis, 1993; Zahorik et al., 2005). The tangent of the initial slope of the performance function is close to unity, and it can be said that for short distances the auditory distance is approximately a linear function of the physical distance. This range of distances is limited to 1–3 m in both real and virtual environments (Békésy, 1949; Bronkhorst and Houtgast, 1999; Brungart, 2001; Zahorik et al., 2005) and it varies depending on both the listener and the listening conditions. For such short distances, Pierce (1901), Ashmead et al. (1990), and Shinn-Cunningham et al. (2000) reported 13%–15%, 5%, and 10% distance judgment accuracy, respectively.[†]

At larger distances (3–48 m), listeners increasingly underestimate the actual distance to the sound source, although the distance judgments are slightly more accurate with implicit (walking toward the source of sound) than explicit (numeric estimation of the distance when both sound source and the listener remain stationary) estimation (e.g., Loomis et al., 1998). In both cases, however, the degree of the underestimation was critically dependent on the availability of specific auditory distance estimation cues (see section 5), the listener's familiarity with the sound source (e.g., Coleman, 1962; McGregor et al., 1985), visibility of the environment, and the listener's expectations. In general, the distance estimates were the most accurate in the case of live talkers (e.g., Békésy, 1949; Cochran et al., 1968; Gardner, 1969). In the case of reproduced speech phrases, the listeners can make relatively accurate estimates to a source playing natural speech but fail when the speech is played backward (McGregor et al., 1985; Wisniewski et al., 2012).

This summary of auditory distance estimation data is based on relatively short distances (less than 50 m) and without consideration of atmospheric conditions since such were the limitations imposed by the data available to date. Examples of test conditions used in major distance estimation studies conducted to date are shown in table 1.

[*] Although results of the majority of the virtual reality (simulated) studies in auditory distance perception qualitatively agree with the results of the studies conducted in real sound fields, Florentine and Epstein (2010) warned that, at least in cases related to sound loudness, ecological validity is important if anyone is going to draw conclusions about sound field perception.

[†] Sound sources used in the cited studies were relatively small in size, and the head of the listener was probably beyond the near field of these sources. This may not be true in the case of larger sources, and their near-field lack of sound pressure uniformity may affect accuracy of listener's distance judgments (e.g., Morse and Ingård, 1968).

Table 1. List of experimental conditions used in selected studies of auditory distance judgments in real environments.[a]

Authors	Distances (m)	Space (Environment)	Sound Sources
Békésy (1949)	1.0–10.0	Closed (anechoic)	Live speech
Edwards (1955)	1.0–8.0	Closed (anechoic)	Metronome
Coleman (1962)	2.7–8.2	Closed (anechoic)	Loudspeakers (impulse)
Coleman (1968)	2.4–8.5	Closed (damped)	Loudspeakers (impulse)
Cochran et al. (1968)	1.0–29.0	Open	Live and recorded speech
Gardner (1969)	1.5–9.1	Closed (anechoic)	Loudspeakers (speech)
Haustein (1969)	1.1–8.6	Closed (real)	Loudspeakers (impulse)
Laws (1972)	0.3–3.0	Closed (anechoic)	Loudspeakers (noise bursts)
Molino (1973)	1.0–16.0	Closed (anechoic)	Loudspeakers (pure tone)
Simpson and Stanton (1973)	0.3–2.7	Closed (anechoic)	Loudspeakers (pulse train)
Mershon and King (1975)	2.7–5.5	Closed (real and anechoic)	Loudspeakers (noise bursts)
Mershon and Bowers (1979)	0.6–8.0	Closed (real)	Loudspeakers (noise bursts)
Strybel and Perrott (1984)	0.5–48.8	Open (discrimination only)	Loudspeakers (noise bursts)
McMurtry and Mershon (1985)	0.75–6.0	Closed (reverberant)	Loudspeakers (noise bursts)
Ashmead et al. (1990)	1.0–2.0	Closed (anechoic)	Loudspeakers (noise bursts)
Nielsen (1993)	1.0–5.0	Closed (anechoic and real)	Loudspeakers
Speigle and Loomis (1993)	2.0–6.0	Open	Loudspeakers (pulse train)
Ashmead et al. (1995)	5.0–19.0	Open	Loudspeakers (noise bursts)
Loomis et al. (1998)	4.0–16.0	Open	Loudspeakers (speech)
Neuhoff (2001)	0.6–12.0	Open	Loudspeakers (synthetic)
Kim et al. (2001)	0.5–5.0	Closed (anechoic)	Loudspeakers (noise bursts)
Kim (2009)	0.5–5.0	Closed (anechoic)	Loudspeakers (noise bursts)
Calcagno et al. (2012)	1.0–6.0	Closed (real)	Loudspeakers (noise bursts)
Wisniewski et al. (2012)	2.0–30.0	Open (recordings)	Loudspeakers (speech)

[a]This list does not include studies performed in simulated environments using recordings played through headphones, such as studies conducted by Anderson and Zahorik (2011), Bronkhorst and Houtgast (1999), Brungart (2000), Brungart and Scott (2001), and Zahorik (2002a).

Specific auditory cues contributing to the listeners' distance estimations are discussed in section 5. The purpose of section 5 is to describe the factors and their limits that facilitate auditory distance estimation judgments outlined in this report. Regrettably, despite an extensive knowledge accumulated to date of auditory distance perception to sound sources located at short and intermediate distances in enclosed spaces (both anechoic and reverberant), it is still unclear to what extent this knowledge may be applied to sound sources located at great distances (100 m and more) in an open field and operating under various atmospheric conditions. It is unknown what role specific auditory distance cues will have under such conditions and how the open field conditions may affect listeners' expectations and perception. Therefore, prior to discussion of specific auditory cues aiding in distance estimation, the next section (section 4) presents an overview of different factors affecting sound propagation in both open and closed spaces.

4. Sound Propagation in Space

The egocentric auditory distance is the apparent distance from a listener to a sound source. This distance is dependent on a number of auditory cues resulting from characteristics of the sound source, abilities of the listener, and factors related to sound wave propagation in the surrounding space. The basic sound source, environment, and listener properties that affect auditory distance estimation judgments in open space are shown in figure 1. In a closed environment, the additional variables are reflections from space boundaries (echoes and space reverberation), while some environmental variables shown in the figure are not present.

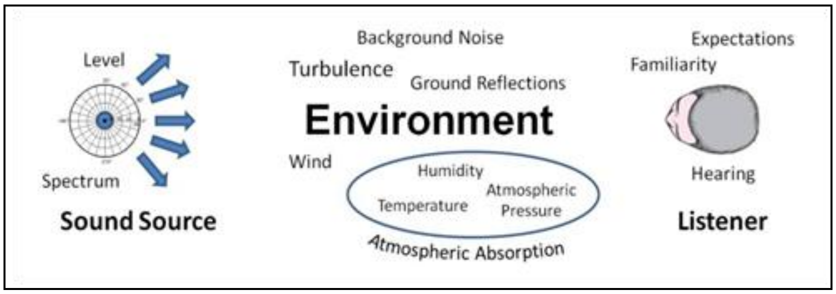

Figure 1. Basic variables that affect auditory distance judgments in an open environment.

Although factors related to the sound source and the listener are not the main subject of this report, they also affect the relationship between the real and perceived sound source and therefore are briefly addressed in the following section.

4.1 Spherical Wave Propagation

For an ideal point source (acoustic monopole) radiating sound energy in an unbound sound field (free field), sound energy spreads in all directions (wave-front spreading), and the sound intensity I at a given point in space is a function of distance r from the sound source

$$I = \frac{W}{4\pi r^2}, \tag{2}$$

where W is the power of the sound source (watts). Equation 2 is commonly referred to as the inverse-square law. This law applies only to the ideal omnidirectional sound source operating in unlimited space and to the ideal medium, which does not attenuate the spread of sound energy.

Based on equation 2, the sound intensity level *i* radiated by the sound source decreases at the rate of 6 dB for every doubling of the distance* from the sound source to the observer (listener) according to the formula

$$\Delta i = 10 log \frac{I_2}{I_1} = 20 log \frac{r_2}{r_1}, \tag{3}$$

where Δi is the difference in the sound intensity level between the sound source location and observation point, and I_1 and I_2 are the sound intensities at the sound source and at the observation point, respectively. The 6-dB rate of sound decay means that sound intensity decreases to one-fourth of its initial value, and sound pressure decreases to one-half its initial value for each doubling of the distance. In calculating sound intensity level (dB IL) and sound pressure level (dB SPL) existing at a specific point in space, the common reference values are I_o = 10^{-12} W/m^2 and $p_o = 10^{-6}$ Pa, respectively. The 6-dB decay per doubling of the distance only applies to free-sound field or anechoic conditions. Typical sound decay outdoors over a soft ground is about 4.5 dB per doubling of the distance. These results apply to only free-sound field or anechoic conditions. In reverberant environments, the decrease is less, e.g., 4.25 dB in a normal room due to sound reflections from space boundaries (Zahorik and Wightman, 2001).

Assuming that the sound intensity at the sound source location is always measured at the distance $\boldsymbol{r_1}$ = 1 m, equation 3 may be reduced to

$$\Delta i = 20 \log (r_2) . \tag{4}$$

Equations 3 and 4 are valid for an ideal sound source operating in a free-sound field but would fail in the presence of reflective surfaces where the sound attenuation with doubling the distance can be expected to be no more than 4–5 dB (e.g., Zahorik and Wightman, 2001).

Real sound sources, unlike the ideal point source, have finite dimensions and cannot be treated as point sources in their proximity. The sound waves produced by various parts of a real sound source interact in the space close to the source's surface. The interaction, which consists of constructive and destructive interference of multiple waves originating from various locations on the sound source's surface, creates a complex pattern of spatial maxima and minima of sound intensity. As a result, close to the sound source's surface the sound intensity does not obey the inverse-square law, and the particle velocity is not in phase with sound pressure. However, at some greater distance from the surface, these separate pressure waves combine to form a relatively uniform front that propagates away from the source. The distance from the sound source where the pattern of spatially distributed maxima and minima merges in a uniform waveform front is approximately equal to the wavelength (λ) of the radiated sound (Morse and

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*In the case of a line sound source, such as a moving train or busy highway producing cylindrical waves, the doubling of distance from the sound source results only in a 3-dB reduction of sound intensity level.

Ingård, 1968). The sound field where the sound source can be treated as a point source and the sound wave can be treated as a plane wave is called the *far field*. The area near the sound source where these conditions are not met is called the *near field*.

Most real sound sources are not omnidirectional and radiate most of their energy in certain specific directions. Such sound sources are directional and can be referred to as dipole, quadrupole, etc. The directionality of the sound source is captured by its *directivity factor Q,* and it needs to be taken into account in calculating the sound intensity existing at a given distance and direction. Factor Q depends on sound frequency and is equal to one (Q = 1) at low frequencies when the wavelength of a sound wave is large in comparison to the dimensions of the sound source, and the sound source is effectively omnidirectional. Factor Q can be as large as 10 for very directional sound sources. The logarithmic form of the factor Q,

$$DI = 10logQ \ , \tag{5}$$

is called *directivity index*, *DI,* and is expressed in decibels. For an omnidirectional sound source radiating into unlimited free space, DI = 0. For the same sound source radiating energy close to an ideal reflective surface (hemispherical radiation), DI = 3 dB (Lamancusa, 2000). To account for sound source directivity, equation 2 can be modified as

$$I = \frac{QW}{4\pi r^2}, \tag{6}$$

where Q is a directivity factor of the sound source. This equation is valid for only the observation point that is located on the main radiation axis of the sound source.

4.2 Atmospheric Attenuation

In a real medium, such as air, sound energy propagating through the medium not only spreads in different directions, but it is also absorbed by the medium, resulting in the exponential decay of energy described as the *inverse exponential power law* known as the *Beer-Lambert law*. According to this law

$$I = I_o e^{-\alpha d}, \tag{7}$$

where I_o and I are sound intensities at the sound source and the observation point, respectively, d is the distance between these two points, and α is the absorption coefficient of the medium. Absorption of sound energy by a medium, called *atmospheric absorption,* is the result of internal friction within the medium that converts acoustic energy into heat. The basic mechanisms of atmospheric absorption are heat conduction, shear viscosity, and molecular relaxation processes (Sutherland and Daigle, 1997). The amount of energy loss caused by these mechanisms depends on sound frequency, temperature and atmospheric (static) pressure within the medium, and in the case of molecular relaxation processes, on humidity of the medium (air). This means that changes in meteorological conditions (weather) have a large effect on sound propagation. Note that although rain, snow, and fog have relatively very small effects on sound propagation, their presence at larger quantities affects air humidity. The relationship between the amount of sound energy absorbed at given frequencies by a medium and meteorological conditions (temperature, atmospheric pressure, and humidity) are complex and nonmonotonic functions, and the actual amount of absorption needs to be calculated for specific combinations of these conditions. For example, sound absorption at 30 °C is greater for relative humidity of 10% than for 40%, while the reverse is true for 15 °C (e.g., Harris, 1966).

Combining equations 6 and 7, we can predict sound intensity in a real medium as

$$I = \frac{QW}{4\pi r^2} e^{-\alpha d} \; . \tag{8}$$

At intermediate distances, up to approximately 200 m (Albert, 2004), and at low frequencies the loss of sound energy due to atmospheric absorption by a laminar (not turbulent) medium is usually small and can be negligible. However, at large distances and high frequencies, energy loss due to atmospheric absorption can be quite large and exceed the loss caused by a three-dimensional spread of energy. The effect of atmospheric absorption on sounds with high-frequency energy above 10 kHz "can become distinctly audible at distances as short as 15 m" (Blauert, 2001).

The relationship between the coefficient of absorption (α), sound frequency, temperature, atmospheric pressure, and relative humidity of the propagating medium can be calculated as

$$\alpha = 8.686 f^2 \sqrt{\tau} \times [\frac{1.84 \times 10^{-11}}{\rho} + \frac{(b_1 + b_2)}{\tau^3} \;] \; , \tag{9}$$

where f is sound frequency in hertz, τ is relative temperature ($\tau = T/T_{20}$ in kelvin; $T_{20} = 293.15$ K), ρ is relative atmospheric pressure ($\rho = p/p_n$ in pascals; $p_n = 101{,}325$ Pa), and b_1 and b_2 are complex coefficients dependent on relative humidity r_h in percent, relative temperature τ, sound frequency f, and relaxation frequencies f_n and f_o of nitrogen and oxygen (see ISO 9613-1:1993(E) and ISO 9613-2:1996 (E) standards, Sutherland and Daigle [1997], or Salomons [2001] for a more detailed description of b_1 and b_2 coefficients).[*] According to this formula, the coefficient of absorption is proportional to the square of frequency and is a complex function of weather conditions. The formula is valid for pure tones and narrowband noises, and it has been used as the basis for the calculations of the atmospheric effects presented in this report. Its accuracy is estimated to be ±10% for $153 < T < 323$ K, $0.05 < h$ (concentration of water in the atmosphere; $h = r_h\,(p/p_n)$) $< 5\%$, $p > 200{,}000$ Pa, and $0.0004 < f/p < 10$ Hz/Pa (Salomons, 2001). An example of dependence of absorption coefficient of frequency for a specific set of environmental conditions is shown in table 2. Note, however, that equation 9 does not take into account the presence of wind and properties of the ground's surface (discussed in the following section).

[*] Relative humidity r_h and relaxation frequencies f_n and f_o are parameters of b_1 and b_2 coefficients.

Table 2. Atmospheric absorption coefficient α (in decibels per kilometer) for the preferred one-third-octave center frequencies f_c (in hertz) (T = 283.15 K (10 °C); r_h = 80%; p = 101,325 Pa [1 atm]).

f_c	25	50	100	200	400	800	1600	3150	6300
	31.5	63	125	250	500	1000	2000	4000	8000
	40	80	160	315	630	1250	2500	5000	10000
A	0.018	0.07	0.25	0.77	1.63	2.88	6.3	18.8	67.0
	0.028	0.11	0.37	1.02	1.96	3.57	8.8	29.0	105.0
	0.045	0.17	0.55	1.31	2.36	4.58	12.6	43.7	157.0

4.3 Ground Effect

Spherical spread of sound energy (equation 2) and atmospheric absorption (equation 7) are two main sources of attenuation of energy of the propagating sound. However, there are also several others. Sound waves propagating close to the ground surface are absorbed and reflected by the ground. This additional factor affecting sound propagation is called *ground effect* or *ground attenuation*. Constructive interactions between direct and reflected sound waves may increase the sound level at the listener up to 6 dB. Destructive interaction may, in the worst case, completely cancel out the sound. In general, the softer the ground, the greater ground attenuation in reference to an ideal reflective surface. The overall amount of ground attenuation depends on the type of ground (ground impedance), sound frequency, distance over the ground between the sound source and the listener, and the heights of both the sound source and the listener above the ground surface. In the case of a grassy field, the ground absorption is most pronounced in the 200- to 600-Hz range and extends toward higher frequencies with increasing distance between the sound source and the listener (Garinther and Thompson, 1993; Lamancusa, 2000; Sutherland and Daigle, 1997). The closer the sound source is to the ground surface, the greater amount of ground attenuation and greater attenuation of energy at higher frequencies. Fortunately, in many cases ground effects are of little consequence for transmission of sound at heights of more than 1.5 m above ground level (Naguib and Wiley, 2001).

The presence of wind and changes in air temperature with level above the ground surface are additional factors affecting sound propagation. Both factors are discussed in the next section.

4.4 Wind and Other Open Space Effects

When sound travels through still air with uniform atmospheric conditions, it propagates in straight lines. However, wind conditions (velocity and direction), as well as temperature, change with altitude (height above the ground), and these changes affect sound velocity and cause sound waves to propagate along curved lines. Under normal sunny conditions, solar radiation heats the Earth's surface, and at low altitudes the atmosphere is warmer, causing a temperature gradient and the sound velocity to be higher in the warmer air. In the evening, the Earth's surface cools down, and the temperature gradient reverses itself. These two respective temperature conditions are called temperature lapse and temperature inversion. Similarly, wind conditions depend on the height above the ground due to the slowing of the wind velocity at the ground surface due to surface friction. This causes a wind gradient, which is analogous to a temperature gradient. When sound velocity decreases with height (upwind sound propagation; daytime sunny warming of the ground), it causes an upward bend of the sound wave (upward refraction) and creates refractive shadow zones with poor audibility for the propagating sound. Conversely, when sound velocity increases with height (downwind sound propagation; evening temperature conversion chilling the ground) it causes a downward bend of sound waves (downward refraction), leading to multiple reflections at the ground surface and resulting in good audibility for the sound over a long range (Heimann, 2003). Upward or downward refraction of sound caused by the wind can decrease or increase the expected sound level at the listener location compared to a no-wind condition by as much as ±10 dB (e.g., Ingård, 1953).

Atmospheric turbulence, i.e., existence of regions of inhomogeneity in air velocity caused by local variations in temperature and wind velocity, also affects sound propagation by scattering sound energy. The changes in sound level caused by atmospheric turbulence can be as large as 20 dB, are time dependent, and are characterized by an increased sound level in acoustic shadow zones. In addition, all solid objects, such as berms, barriers, and towers that are in the path of the propagating sound, disrupt natural propagation of sound energy, causing frequency-dependent diffraction and reflection of sound energy. In the case of trees and forests, their sound attenuation effect is usually negligible and should only be taken into account at high frequencies (5 dB per 30 m at 4000 Hz [Aylor, 1972]). For frequencies above 2 kHz, sound attenuation caused by dense forest made of large trees (e.g., jungle) can be estimated as (Bullen and Fricke, 1982)

$$\Delta I\ d = 8.5 + 0.12D\ , \tag{10}$$

where D is the depth of an infinitely wide belt of forest* (in meters). This estimation is somewhat higher, but not much, for grassy areas. All these phenomena and mechanisms affect propagation of sound energy in the open space and ultimately affect sound source distance estimations.

4.5 Closed Space Effects

In closed spaces, reflections from space boundaries distort the smooth decrease of sound intensity with the increasing distance from the sound source. Early sound reflections may cause local reinforcement or decrease in sound energy in various locations in the space, while the late and multiboundary reflections fuse together, forming a characteristic delayed trace of sound called reverberation. Reverberant energy is roughly independent† of the distance from the sound source and can even dominate the overall sound energy at large distances from the sound source. According to the Hopkins-Stryker equation (Hopkins and Stryker, 1948), sound intensity at a given point in a closed space is equal to

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*This is an empirical formula predicting the amount of sound attenuation (in decibels) caused by a certain thickness of a belt of trees.

†This cannot be said about early reflections, which depend on the position of the sound source in the space.

$$I = W(\frac{Q}{4\pi r^2} + \frac{4}{R}) , \quad (11)$$

where the first element (W) is the sound intensity of a direct sound, and the second element (Q) is sound intensity of the reverberant field caused by space reflections. R is the room constant (in square meters) dependent on total absorption of the space boundaries.

$$R = \frac{aS}{1-a} , \quad (12)$$

where S is the total area of room boundaries (square meters) and a is the average sound absorption coefficient of room surfaces. The farther from the sound source, the smaller the contribution of direct sound energy and the greater the contribution of reverberant energy to the overall acoustic energy in the space. At some distance from the sound source, the contributions of direct and reverberant (reflected) acoustic energies are equal; this distance is called the *critical distance*, d_c , which can be calculated from the equation 11 as

$$d_c = 0.141\sqrt{QR} , \quad (13)$$

or as (Davis and Davis, 1987)*

$$d_c = 0.057\sqrt{\frac{QV}{T}} , \quad (14)$$

where V is space volume (cubic meters), T is space reverberation time (seconds), Q is directivity of sound source (dimensionless), and R is room constant expressed in square meters. The relative amounts of direct and reflected energy heard in the room affect the listener's perception of the distance to the sound source. In the case of directional sound sources, the direct-to-reverberant ratio of sound energy depends on an angular deviation of direction from the main emission axis of the sound source, which may cause the directionality of the sound source to affect auditory distance judgments when they are made from various sides of the sound source.

5. Auditory Distance Estimation Cues

Properties of a sound source and the acoustic phenomena resulting from sound propagation through the environment (see section 3) result in several auditory distance cues available to the listener. Depending on the state of motion of both the sound source and the listener, the auditory distance estimation cues are usually classified as static cues (static sound source and listener) and dynamic cues (moving sound source or listener) (e.g., Devallez, 2009; Lu et al., 2007). The five basic *static cue*s include sound intensity, direct-to-reverberant energy ratio, sound spectrum, level of background noise, and auditory parallax (interaural differences). The *dynamic cues*

*This derivation is based on an empirical relationship (not a physical equation) between the *RT* (reverberation time) of a room(s), its volume (cubic meters), and its total absorption (square meters), as established by Sabine (1922).

include motion parallax and the acoustic tau effect (estimated time to contact). Note that static cues operate both in static as well as in dynamic situations (when the observer or the sound source moves).

An important characteristic of the distance cue is the absolute or relative character of the cue. Absolute cues are those that do not require the listener's familiarity with the sound source and surrounding environment in making distance estimates. Relative cues are those that do. Sound intensity, sound spectrum, and background noise are examples of relative cues, whereas the amount of reverberation and motion effects are considered the absolute cues. To make an informed (relatively accurate) distance judgment using relative cues, the listener must be familiar with the sound source (have a priori knowledge about sound emission level) and surrounding environment. A prime example of a relative cue is sound intensity. Sound intensity alone is insufficient for the listeners to determine the actual distances to an unfamiliar sound source since its original sound intensity is unknown to the listener (e.g., Kerber et al., 2004; Nielsen, 1993). However, with increasing familiarity with both a given sound and surrounding environment, the distance judgments based on sound intensity can become quite accurate (Coleman, 1963; Haustein, 1969).

Other nonspecific factors contributing to auditory distance estimates are the listener's expectations and experience, and available nonauditory cues (e.g., visible objects). For example, whispered speech (produced typically at a level of about 30-dB SPL at 1 m) is expected by the listener to come from a nearby sound source, whereas normal (conversational) speech (65-dB SPL at 1 m) and a shout (90-dB SPL at 1 m) are expected to come from much larger distances (e.g., Brungart and Scott, 2001; Gardner, 1969). For example, Philbeck and Mershon (2002) presented whispered, conversational, and shouted speech from a loudspeaker located 2.5 m from the listeners, and the average distance estimations reported by the listeners were 0.76, 1.52, and 3.05 m, respectively, for each type of speech. All sounds were presented at the same sound intensity level. Therefore, it should be expected that the distance to artificially amplified whispered speech produced by a distant sound source will most likely be greatly underestimated by the listener because a whisper is expected to come from a relatively close distance.

Many acoustic phenomena affecting auditory distance judgments also affect other perceptual sensations, such as loudness and timbre. While relationships between auditory distance, loudness, and timbre are of scientific interest and have led to numerous investigations (e.g., Békésy, 1938; Coleman, 1963; Mohrmann, 1939; Warren, 1963), perceived distance, loudness, and timbre are separate perceptual attributes of auditory events, and there is no causal relationship between them. However, when the perceived distance to an unknown sound source cannot be determined by the listener as such, then sound loudness or timbre are frequently used by the listener as a substitute in deriving arbitrary distance judgment (e.g., Coleman, 1962).

5.1 Sound Intensity

Sound intensity is the most natural auditory distance estimation cue. It operates on the principle that the lower the intensity of sound reaching the listener, the farther away the source of sound. This cue is available in all listening situations and for all audible sounds regardless of the distance from the listener. In addition, while perceived sound intensity depends on the direction toward the sound source, perception of changes of sound intensity with distance to the sound source are relatively direction independent (e.g., Shinn-Cunningham, 2000a).

The main limitation of the sound intensity cue is that it is a relative cue (Mershon and King, 1975; Nielsen, 1993). A change in the intensity of an arriving sound informs a listener of a change in the distance to an otherwise invariable sound source (Mershon, 1997). Perception of changes in sound intensity is useful in distance discrimination studies, but it is not useful for the absolute estimation of the distance. The distance to a perceived unknown sound source estimated on the basis of sound intensity alone is practically independent of the distance to the actual sound source (Blauert, 2001). The listener needs to be familiar with the sound source and the effects of environment on changes in sound intensity in order to be able to use sound intensity as an absolute cue (Coleman, 1962; McGregor et al., 1985). This means that for sound intensity to be an absolute distance cue, the listener must know the sound intensity produced at the ear by the sound source located at a known distance in the actual environment (Blauert, 2001). Coleman (1962), Gardner (1969), and Mershon and King (1975) demonstrated that in the case of unfamiliar sounds produced in anechoic space, i.e., in a neutral environment, the sound intensity cue does not allow the listener to make meaningful distance judgments. For unfamiliar sound sources, the perceived distance to the sound source is generally undefined,[*] and distance judgments are predominantly made only on the basis of sound loudness and timbre (as a substitute for an estimated distance) and not on the actual distance to the sound source (Blauert, 2001). This agrees with the finding that the perceived distance function for synthetic stimuli (tone, burst of noise) can be approximated by an exponential function of physical distance with an exponent of about 0.3 (e.g., Petersen, 1990; Zahorik, 1997). Note that exponential function with 0.3 exponent is a close approximation of the loudness growth function.

Familiar sound sources, especially familiar voices of live talkers, allow sound intensity to be a much more effective cue in auditory distance judgments and result in a higher than 0.3 exponent (Mershon and Philbeck, 1991; Philbeck and Mershon, 2002). Additionally, in the case of speech sound sources, the perceived distance to a sound source is affected differently by the actual production level of the sound source (perceived distance increases with the signal level) than by the presentation level (no differences in vocal effort) at the ear (perceived distance is

[*]When listeners are asked to make judgments of perceived distance to sound sources with no distance cues (e.g., unfamiliar sound in an anechoic condition), the sound sources are typically perceived to be at a default distance (Mershon and King, 1975). This phenomenon, called *specific distance tendency*, was first observed in perception of visual distances (Gogel, 1964). Gogel (1969; 1973a; 1973b) reported that in the case of vision, such distance is about 2 m. Zahorik (2002a) estimated the *specific auditory distance* to be about 1.5 m, while according to the data reported by Haustein (1969), it seems to be close to 3.0–4.0 m. It may be hypothesized that the concepts of *auditory horizon* (see section 1.2) and *specific auditory distance* are closely related.

independent of or decreases with the signal level) (Brungart and Scott, 2001). This difference is due to the fact that production level is affected by vocal effort, while presentation level is not. A related phenomenon is called the *loudness constancy* effect, which recognizes the fact that the sound intensity of a sound source is perceived as constant when the sound intensity (loudness) changes at the ear because of changes in the distance to the sound source (e.g., Fieandt, 1951; Zahorik and Wightman, 2001).

As discussed in section 3, the sound pressure of a spherical sound wave propagating in an open field, or in an anechoic environment, decreases by 6 dB per doubling of the distance from the sound source. Therefore, a change in sound level by 6 dB produced by a known sound source should be associated with the doubling of the estimated distance. However, such expectation is incompatible with the results of experimental studies in which "the reduction of 20 dB, rather than expected 6 dB, leads to a doubling of the distance to the auditory event" (Blauert, 2001). According to these studies, a change in the sound intensity level required to double the perceived distance in an anechoic space seems to be on the order of 15–20 dB (e.g., Békésy, 1949; Gardner, 1969; Mershon and King, 1975; Petersen, 1990; Nielsen, 1993; Sheeline, 1982) for intermediate physical distances where no environmental effects are yet to be expected (see table 1). A general conclusion resulting from this data supports the notion that auditory distance judgments made for intermediate distances (3.0–10.0 m) on the basis of the sound intensity cue alone significantly underestimate distances to real sound sources until listeners are sufficiently familiar with the sound sources.

The smallest change in sound intensity that can be perceived as a change is called the just noticeable difference (jnd) or difference limen (DL). In open natural sound field environments, such change is equal to 1–3 dB and becomes smaller, on the order of 0.5–1.0 dB in anechoic spaces or in listening through earphones for narrowband stimuli, and even less for wideband stimuli. Therefore, the listener's ability to detect a change in distance on the basis of intensity alone is in the order of 0.5–3.0 dB (Little et al., 1992)—that is, 5%–30% depending on the type of space and background noise level. These values (typically ~10%) were reported in several distance discrimination studies (e.g., Ashmead et al., 1990; Budzynski, 1986; Edwards, 1955; Simpson and Stanton, 1973; Strybel and Perrott, 1984; Zahorik et al., 2005). These values also agree with the data reported by Haustein (1969), who measured perceived distance to a known sound source located in the 1.1- to 8.6-m range, and reported judgment uncertainty from ±0.45 m to ±0.55 m for all distances except the 1.1-m distance, where the judgment uncertainty was about half that value. Slightly smaller values of 3.5%–6% have been reported by Strybel and Perrott (1984) in open space experiments.

5.2 Reverberation and Echoes

The amount of reverberation and echoes in a perceived sound is another auditory distance cue. This cue is only available in spaces where sounds reflect from space boundaries and create reverberant energy that is mixed with the direct energy of the active sound source. In reverberant spaces, the amount of reflected energy in an overall sound is roughly independent of the sound source signal level, and while the direct energy of the sound source decreases with the distance from the sound source, the reverberant energy is fairly constant across space (e.g., Shinn-Cunningham, 2000a). Therefore, the direct-to-reverberant energy ratio (DRER) gradually decreases with increasing distance from the sound source; it reaches an asymptotic value at far distances from the sound source and close to the room boundaries.*

Békésy (1938) should probably be credited as the first to indicate that the decrease in the DRER produces a sensation of increasing distance to a sound source, and that the DRER can serve as an auditory distance cue. This cue is also considered an absolute distance cue that is equally effective in determining perceived distance to known and unknown sound sources since it does not require previous knowledge about the sound source (e.g., Mershon and Bowers, 1979; Mershon and King, 1975; Sheeline, 1982). In contrast, the use of this cue requires the listener to have prior knowledge of the surrounding space. However, no evidence of space adaptation by listeners has been observed in the conducted studies. Apparently, listeners can very quickly acquire spatial properties of a surrounding space (Plenge, 1974) and use energy reflected from the space boundaries to determine the distance to the sound source regardless of the intensity of the original sound (Bronkhorst and Houtgast, 1999). In this context, some outdoor conditions, such as forest or jungle environments, create their specific echoes and reverberation, and the DRER cue may also be effective in such outdoor environments (Albert, 2004; Richards and Wiley, 1980).

Numerous auditory distance estimation studies conducted after Békésy (1938) confirmed that auditory distance judgments made in reverberant spaces lead to more accurate distance judgments (although generally still underestimating real distances) than distance judgments made in anechoic and open field environments (e.g., Mershon and King, 1975; Mershon and Bowers, 1979; Mershon et al., 1989; Nielsen, 1993; Sheeline, 1982; Shinn-Cunningham, 2000b; Wagenaars, 1990). Even in the case of sound sources reproduced through earphones, the distances to sound sources recorded in an anechoic space seem to be underestimated more than the distances to the same sound sources recorded in reverberant spaces (e.g., Bergault, 1992; Butler et al., 1980). However, Zahorik (2002a) observed that in the case of familiar speech signals presented in a reverberant environment, the intensity cue was weighted more by the listeners than the DRER cue in estimating the distance to a sound source. This relation was reversed in the case of unfamiliar sounds. It also needs to be mentioned that in the case of highly reverberant conditions (RT > 1.5 s), the listeners began to overestimate the distance to the actual sound source (e.g., Cabrera and Gilfillan, 2002; Mershon et al., 1989).

One difficulty with quantifying the effects of the DRER on the accuracy of auditory distance judgments is the lack of clarity regarding the basis that listeners use to differentiate various

*At short distances from the sound source, this regular relation may be affected by directionality of the sound source and the presence of early reflection from space boundaries.

values of the DRER. Although several authors suggested various criteria for calculating the DRER, no single criterion for DRER quantification appears to be consistent with all reported results, and no generally accepted standard has emerged to date. For example, Larsen et al. (2008) identified four phenomena that covary with the DRER—namely, interaural cross-correlation (IACC), spectral variance, spectral envelope, and temporal integration—and reported that listeners can discriminate changes in these parameters. The cited authors asserted that listeners can use any or all of these parameters. However, if the listeners base their judgment on temporal integration, then the question remains, How should sound energy be integrated in direct and reverberant energies to calculate the effect of the DRER on auditory distance estimations? For example, should a specific architectural acoustic criterion, such as C50, C80, D, EDT10, etc. (e.g., Carvalho, 1994), be appropriate? The durations involved in these criteria seem too long, and some authors have suggested a duration of 2.5–3.0 ms determined on the basis of the "approximated duration of anechoically measured head-related impulse responses" (Zahorik, 2002c; see also Larsen et al., 2008).

Bronkhorst and Houtgast (1999) developed a model that proposes the use of a 6-ms integration window when calculating the energy of direct sound and treating all energy arriving after 6 ms as reverberant energy. The authors reported that this model predicts their own data as well as the data reported by Nielsen (1973), Mershon and Bowers (1979), and Wettschureck et al. (1973) and also accounts for the presence of an *auditory horizon* in reverberant spaces. This model was later modified by Bronkhorst (2001; 2002), who replaced the 6-ms integration time by an interaural time difference (ITD) based on room impulse response.

Actually, any of the sound field parameters that remain constant in the reverberant field (IACC, reverberant field intensity, etc.) can account for the presence of the acoustic horizon. Larsen et al. (2008) also stated that in reverberant environments "sources well beyond critical distance should be judged to be closer than they actually are because the signal reaching the listener's ears is very similar to the signal of a closer sound source, which explains the compression of the perceived distances." Recently, Lu and Cooke (2010) suggested a criterion based on estimating the ratio of energy arriving from the direction of the sound source to the overall energy at the listener's location. However, no standard criterion to quantify the DRER has been established yet.

Another difficulty with quantifying the effects of the DRER is limited information available about the effects of specific DRERs on sound source perception. Changes to the DRER of an arriving signal affect the timbre of the signal, the audibility of temporal modulation in the signal (e.g., speech), and the signal's perceived duration. Further, the interaction between reverberant content and overall intensity of sound varies from space to space (Ashmead et al., 1990; Nielsen, 1993). It seems that a short reverberation time (RT) leads to underestimation, and a long RT leads to overestimation of the actual distance to the sound source (Mershon et al., 1989). Sheeline (1982) observed that auditory distance estimations are more accurate in cases when the DRER is in range of 9–18 dB but become less accurate if the DRER drops below 9 dB. Sakamoto et al. (1977) observed that when the time delay of the first reflection was longer, the perceived distance to a given sound source was larger. The authors studied reflection, coming from ±30°, ±60°, ±90°, and ±135° angles regarding the direction faced by the observer, and also reported that the reflection coming from ±60° contributed the most to the perception of distance. According to Larsen et al. (2008), people can differentiate DRERs when they change by 2–3 dB or more. Larger values of 5–6 dB were reported by Zahorik (2002c). This indicates that under some conditions, the DRER may be a bit less effective as a relative cue than sound intensity; this may also limit its precision in making both relative and absolute distance judgments under these conditions. The relatively low resolution of perceived DRERs may also imply that this cue may be unreliable when used to judge the distances to a moving sound source. However, overall, this cue is the main distance estimation cue used by the listeners in the case of judging distances to unfamiliar sounds in reverberant spaces.

5.3 Sound Spectrum

Another relative distance cue that requires familiarity with the sound source is sound spectrum. As described in section 3, atmospheric absorption and weather conditions of the environment affect both the intensity and spectrum of sound propagating for distances as short as 15 m (e.g., Blauert, 2001). High-frequency sounds are attenuated at a higher rate than the low-frequency sounds. The amount of loss can reach 3–4 dB per 100 m at 4000 Hz (Ingård, 1953). The sound spectrum is also affected by the reflective properties of the space boundaries. All these effects cause coloration of the propagating sound at larger distances mostly by reducing the high-frequency content of the sound. Sounds lacking high-frequency energy are perceived as being emitted from more distant sources than sounds rich in high-frequency content (Bloch, 1983; Butler et al., 1980; Kopčo and Shinn-Cunningham, 2011; Levy and Butler, 1978). For example, several authors have reported that low-pass filtered sounds are perceived as being produced by more distant sound sources than sounds having unmodified spectrum with high-frequency content or high-pass stimuli[*] (Coleman, 1968; Levy and Butler, 1978; Lounsbury and Butler, 1979; Butler et al., 1980; Little et al., 1992). Even if the listeners are not very familiar with the specific sound, they quickly learn its properties, and their accuracy increases markedly in successive trials (Little et al., 1992; McGregor et al., 1985). However, the use of spectral cues may be limited in reverberant environments where early reflections can modify the spectrum of perceived sound in a way inconsistent with the distance to the sound source.

Note, however, that the sound spectrum cue works differently for nearby and faraway sound sources and can be at times confusing (Coleman, 1968). For sound sources relatively close to the listener, the increase in distance emphasizes the high-frequency content of the sound due to the shape of the equal-loudness functions and the scattering effect of the head and torso (Brungart et al., 1999). In contrast, the increase in distance for faraway sound sources emphasizes the

[*] In the case of narrowband and harmonic sounds, it also can be expressed in terms of the perceived sound frequency.

low-frequency content of the sound due to greater atmospheric (air) absorption of high-frequency energy. This is the reason that warning systems for long-distance acoustic communication are low-frequency systems (e.g., foghorns).

5.4 Background Noise

Background noise is another cue used by listeners to judge auditory distance. Poor signal-to-noise ratio (SNR) is normally associated with a farther distance to a sound source. However, at the same time, background noise existing in a reverberant environment masks some reverberant energy, causing an impression that the DRER is higher and the sound source is closer (Naguib and Wiley, 2001). Mershon et al. (1989) investigated the effect of noise level (45 and 65 dB A-weighted) on distance estimation in reverberant spaces and reported that the presence of noise decreased the perceived distance. In a similar study McMurtry and Mershon (1985) used high-level background noise (90 dB A-weighted) and reported that the noise at this level significantly decreased the accuracy of judged distances. Similar judgments made with added hearing protectors were equally inaccurate, indicating that the use of hearing protectors in noise has no effect on auditory distance judgments. In contrast, Cabrera and Gilfillan (2002) observed a positive effect of noise level on the general overestimation of the distance to talkers in a simulated environment with RT = 2.5 s.

5.5 Auditory Parallax (Interaural Differences)

The closer the sound source is to the head of the listener, the greater the curvature of the sound wave arriving at the head and the greater the shadowing effect of the head. Therefore, the closer the sound source is to the head, the greater the interaural intensity difference (IID) between the ears. However, the IID is a useful distance cue only in the case of nearby sound sources because interaural differences (IID and ITD) do not vary with distance for far-field sound sources (Shinn-Cunningham, 2000a). These differences are the largest along the interaural axis and decrease to zero in the median plane. For example, Holt and Thurlow (1969) have shown that listeners who faced a nearby sound source were unable to judge the distance to the sound source but could properly differentiate the distances when the sound source was at their side.

The IID differences resulting from the changes in the distance to a sound source located in the proximity of the listener's head have been referred to in literature as *auditory parallax*.[*] Several authors have modeled short-range interaural differences using a spherical model of the human head and concluded that auditory parallax can be an effective auditory distance cue in both real and virtual reality environments (Brungart et al., 1999; Hartley and Fry, 1921; Hirsch, 1968; Kim et al., 2001; Lambert, 1974; Molino, 1973). Auditory parallax is also an absolute distance cue since the perception of IID changes is not dependent on the listener's familiarity with the sound source.

[*] The term *parallax* means an apparent displacement of an object.

Acoustical measurements made with real listeners and spherical head models have shown that the IID changes near the head of the listener are quite large, up to a distance of 1.0–1.5 m away from the head beyond which they become quite small and disappear (Békésy, 1949; Bergault, 1994; Kim et al., 2001; Nishimura and Sasaki, 2004; Sone et al., 1992; Suzuki et al., 1998). For example, Hartley and Fry (1921) reported that for a spherical model of the human head, the IID for pure tone stimuli can vary as much as 20 dB between 8.75 and 17.5 cm away from the listener's head. Brungart and Rabinowitz (1999) reported 20+ dB differences for a 3-kHz tone sound source moving away from the head from 0.12 to 1.0 m. Shinn-Cunningham (2000a) reported similar differences for various lateral angles and reported changes in sound intensity level varied at a 10-cm (20-cm) distance from 10 dB (8 dB) at a 30° angle to 25 dB (15 dB) at a 90° angle. Laws (1972) demonstrated that listeners could differentiate between loudspeakers emitting white noise, located at 25 cm and 3 m in an anechoic space, even when both signals had the same sound intensity at the ear. Several other authors also reported effectiveness of auditory parallax in near field in the absence of sound intensity and reverberation cues (e.g., Békésy, 1949; Haustein, 1969; Sone et al., 1992). They reported that auditory parallax can work effectively up to even 2–3 m. In contrast, the ITD varies considerably less with distance under the same listening conditions, and it is not an efficient distance estimation cue. More information about IID and ITD can be found elsewhere (Letowski and Letowski, 2012).

5.6 Motion Parallax

All auditory distance cues just described are static cues that are available to stationary listeners. Movement of the listener enhances auditory distance information available to the listener by utilizing two additional distance cues: absolute and acoustic tau (discussed in section 5.7). The motion parallax cue is the change in angular direction to the stationary sound source as the listener moves at an oblique angle to the direction toward the sound source. The closer the sound source, the larger the change in the direction and the stronger the cue. This situation is shown in figure 2. A similar situation occurs when the sound source moves and the listener remains stationary (principle of reciprocity). However, when both the listener and the sound source move, this does not hold true and the situation is ambiguous.

Speigle and Loomis (1993) reported that combining motion parallax cues with static cues marginally improved the accuracy of listeners' distance judgments. It is plausible that the dynamic distance estimation cue rising from a linear movement of the listener could also be produced by a head rotation of the stationary listener. However, no existence of such a cue related to head movements was observed in either far-field (Cochran et al., 1968) or near-field (Simpson and Stanton, 1973) of the listener. The former result should be expected since there are no binaural distance cues operating in far field. The observations made by Simpson and Stanton (1973) support also the notion that head movements do not facilitate the estimation of distance to nearby sound sources. It may be also true, as Howard (2012) suggested, that motion parallax is generally a weak distance cue in the case of judging auditory distance to nearby sound sources.

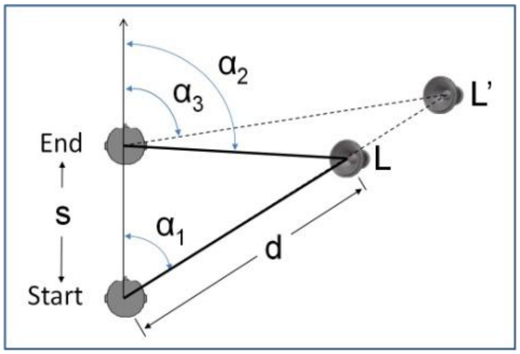

Figure 2. Acoustic source (L) is heard from different directions as the listener moves along distance s. The change in perceived direction becomes smaller when the sound source (L') is located farther away.

5.7 Time-to-Contact (Acoustic Tau)

Another potential dynamic cue that is available for distance estimation to a sound source moving at a constant velocity and is on a collision course with the stationary listener is the time-to-contact, or acoustic tau, cue (Ashmead et al., 1995; Rosenblum et al., 1993; Shaw et al., 1991; Schiff and Oldak, 1990). When the velocity of the sound source is constant, the predicted time to contact is based on changes in sound intensity* and is proportional to the distance of the listener to the sound source (Neuhoff, 1998; 2001). This cue is an auditory analog of visual time-to-contact (optic tau) cue (Lee, 1980). Shaw et al. (1991) hypothesized that in the case of a sound source spherically radiating sound and approaching the stationary listener with a constant velocity in an open field, time to contact can be derived by the listener on the basis of the ratio of sound intensity (*I*) to its rate of change

$$\tau = \frac{2I}{\frac{dI}{dt}} \; . \tag{15}$$

Since the ratio of sound intensity to the rate of change of sound intensity is independent of sound intensity itself and is the same for any sound source, the degree of familiarity with the sound source does not affect a distance estimation judgment. Momentary distance to the sound source is subsequently the product of acoustic tau and the velocity of the sound source (Loomis et al., 1998).

A number of studies were conducted to determine if the listener can use information provided by a moving sound source or moving listener to estimate the distance to an approaching† (being

*Changes in sound intensity are the most important factor of the acoustic tau clue, but sound source movement is also associated with changes in sound spectrum and signal-to-noise ratio.

†Neuhoff (1998; 2001) observed that the changes in sound intensity of a sound source moving away are less noticeable to listeners than the similar changes in the sound source approaching the listener. The approaching sound sources "were perceived as starting and stopping closer than equidistance preceding sounds."

approached) sound source. Schiff and Oldak (1990) presented a sound source approaching a stationary listener at a constant velocity and turned the sound off between 1.5 and 6.5 s before the sound source would reach the listener. The listeners' task was to press a key at the time when they thought the sound source would arrive at their location. The time judgments were roughly inversely proportional to the sound source velocity. However, in most cases the listeners underestimated the time to contact (the key was pressed too early), and the degree of underestimation was proportional to the duration of the silent pause before the expected time of arrival. In addition, blind listeners were more accurate than sighted listeners.

A similar study with similar general conclusions was reported later by Rosenblum et al. (1993), who used recordings of approaching cars presented over earphones and concluded that acoustic tau is the most dominant dynamic cue. Ashmead et al. (1990; 1995) and Speigle and Loomis (1993) used a reverse procedure where the sound source was stationary and the listener moved toward the source. They also demonstrated that acoustic tau is a useful dynamic cue although it leads to underestimation of the distance to nearby sources. Speigle and Loomis (1993) concluded that despite the poor accuracy of acoustic tau, it is still a helpful cue for a listener. Guski (1992) also reported the poor accuracy of the acoustic tau cue, and that listeners using this cue underestimated distances by 44%–77%.

5.8 Summary

The general rules governing auditory distance estimation to nearby and intermediate sound sources have been described in section 3. In their context, it is important to understand how specific distance cues contribute to distance judgments, both individually and synergistically, especially that none of these cues is very reliable alone and some of them require a priori knowledge about the sound source.

The analysis of individual cues conducted in sections 5.1–5.7 can be summarized as that the two main distance cues are sound intensity and reverberation (DRER) and they work best when the listener is familiar with the sound source. Barnecutt and Pfeffer (1998) assessed the perceived distances to both familiar and unfamiliar sounds reproduced over headphones and observed that the sound intensity cue was used in 52.7% and 25.3% of cases, respectively. They suggested that auditory distance estimates may depend on the past experience of the listener in the meaning of perceived sound.

In reverberant spaces where both cues are present, the DRER is generally the dominant cue. Butler et al. (1980) and Mershon and King (1975) compared distance estimations made to the same sound sources in anechoic and reverberant conditions and concluded that apparent distances in reverberant space far exceeded distances in an anechoic space and were more accurate. Pazuchanics (2004) studied combinations of sound intensity, sound spectrum, and the amount of time delay in sound offset after the presentation of a visual cue and concluded the final effect of these cues is a linear combination of individual effects. Zahorik (2002a) assessed joint effects of sound intensity and the DRER cues and proposed a similar integration function based on a weighted "linear combination of logarithmically transformed perceived distances to physical distances." However, he also observed that the weights assigned to individual cues depend to a large degree on the sound type, sound direction of arrival, and to some extent on the actual distance to the sound source. Kopčo and Shinn-Cunningham (2011) noted large differences in conclusions resulting from various distance estimation studies and added that it is most likely that different listeners may weigh the same distance estimation cues differently in different listening situations.

Kopčo and Shinn-Cunningham (2011) studied the joint effects of the DRER, sound spectrum, and auditory parallax (IID) cues on distance estimations to sound sources located in the reverberant near field (0.15–1.7 m). They reported that both the DRER and IID cues contributed to estimates made for sound sources located in a lateral direction, and that the DRER cue facilitated distance responses for sound sources located in front of the listener. Their conclusions support the notion that the DRER is an omnidirectional cue, and the IID cue is only useful in the case of the lateral sound sources. Lateral judgments were relatively accurate, but the listeners overestimated the distances to the frontal sound sources, especially for high-frequency sound sources. In addition, Neuhoff et al. (2012) reported that the estimated distance may be affected by the strength and physical fitness of the listener. In this context it is unclear how age affects auditory distance estimation accuracy, but Hill and Mershon (1985) reported that in the case of visual estimation, older listeners underestimate distance more.

There are many reports indicating that a listener (and observer in the case of visual object) is more accurate during dynamic than static distance estimation (visual estimation: Fukusima et al., 1977; Loomis et al., 1992; Rieser et al.,1990; Thompson, 1983; Speigle and Loomis, 1993). Lu and Cooke (2010) simulated various listening conditions and reported that a combination of motion parallax and time-to-contact information forms an effective distance estimation cue.

The presence of visual cues increases the accuracy of auditory distance judgments and lowers their variability (e.g., Anderson and Zahorik, 2011; Calcagno et al., 2012; Zahorik, 2001). However, when an object that makes a sound is hidden or not obvious and a dummy object that could potentially be a sound source is visible, people report that they hear the sound from the visible object[*] (e.g., Gardner, 1968; Mershon et al., 1980). This effect is known as *ventriloquism* or *visual capture* (Howard and Templeton, 1966). In addition, the relative size of a sound source (real or intended) that is perceived or imagined may affect a listener's perceived distance to the sound source (e.g., Barnecutt and Pfeffer, 1998).

The presented analysis of the literature indicates that making accurate auditory distance judgments is a learned skill that most people only develop to a small degree. Intersubject variability observed in most of the auditory distance estimation studies was large and larger in

[*]This is one of the demonstrations of the *visual dominance* effect (Posner et al., 1976). For example, Colavita (1974) reported that in the case of simultaneous visual and auditory stimulation, people are usually reporting visual stimulation only and are frequently unaware of the presence of simultaneous auditory stimulus.

anechoic than reverberant spaces (e.g., Mershon and King, 1975; Nielsen, 1993; Zahorik et al., 2005). Mershon and King (1975) reported standard deviations equal to approximately half of the range of judged distances in reverberant spaces and about equal to the range of judged distances in anechoic spaces. Laws (1972) and Nielsen (1993) reported standard deviations of distance judgments in anechoic spaces to be about 70% of the distance.

Practice and training in making distance judgments lead to greater familiarity with listening situations and more accurate distance judgments (e.g., Shinn-Cunningham, 2000b). Experienced hunters and archers to whom distance estimation is one of the fundamental skills of the trade are especially accurate in making such judgments. However, in some cases the accuracy of distance judgments may be affected by assumed esthetic criteria regardless of the amount of training. For example, Ekman and Berg (2006) reported that sound engineers have a general tendency to overestimate the actual distance to a sound source in recordings made in a concert hall, while the musicians have the tendency to underestimate such a distance.

6. Distance Estimation in an Open Field

The difficulty of making auditory judgments of distance to a sound source in an open space has been recognized for many years even in relation to relatively short distances (Coleman, 1962; 1963). This difficulty dramatically increases in larger spaces and for greater distances. From all the auditory cues discussed previously, only sound intensity, sound spectrum, and level of background noise can be used by the listener in a large open field. The only sound reflections available to the listener in open space are the ground reflections, which are dependent on the form and type of terrain. However, these reflections create a confusing pattern of interferences rather than providing a helpful distance cue to the listener. Still, such an open space is an easier environment for making accurate distance judgments than an urban setting, which is very confusing because of multiple strong reflections coming from unrelated surfaces (e.g., urban canyon).

Distance estimation in a large open space requires that the listener know the characteristics of the sound at the source and the types of degradations affecting the sound propagation through the space. Further, the listener must possess the skill to hear the changes in the sound and quantify the distance to the source. To do this, the listener needs to be familiar with the sound at the source and be able to hear and identify the specific changes in sound characteristics so he/she can determine the distance needed to produce those perceptual changes. In respect to sound propagation through space, the sound is degraded by overall attenuation, frequency-dependent attenuation (coloration), reverberation (in woods), and fluctuations in level. In general, it is possible to measure and quantify each of these four kinds of signal changes and even develop a single composite measure of these effects (e.g., Brown and Handford, 2000), but their effects on auditory distance judgments would still be unknown because of missing field data.

To address the existing gap in understanding auditory distance estimation in open space, we conducted a field study collecting auditory distance estimation data at distances from 25 to 800 m. Two questions were sought to be answered:

1. What is the accuracy of a distance judgment to natural sound sources located at various distances?
2. Is there any specific distance at which the listeners expect a given sound source to be located (i.e., are there any specific distances that dominate the listeners' responses regardless of the actual distance)?

To our knowledge, this is the first study of its kind. We had to impose several limitations on the extent of the study and selection of experimental conditions. For example, the study was limited to stationary conditions of both the sound source and the listener. Also, the study was conducted under relatively stable weather conditions and only for sound sources located in front of the listener. These specific limitations will be evident in the description of the study detailed in the following section. We refer to this study as the Spesutie Island Study, in reference to the place where the experimental data were collected.

6.1 Spesutie Island Study: Study Description

The Spesutie Island Study was conducted at Spesutie Island, MD, on the outdoor test area known as the EM Range. The EM Range is an open field approximately 900 m long and 200 m wide. The range is flat, covered with grass, and includes a sand/gravel track encircling the grassy area. Three sides of the area are surrounded by young trees and bushes, and the fourth side is separated by an additional 50 m of grassy area separating the EM Range from a local road. The general view of the area is shown in figure 3.

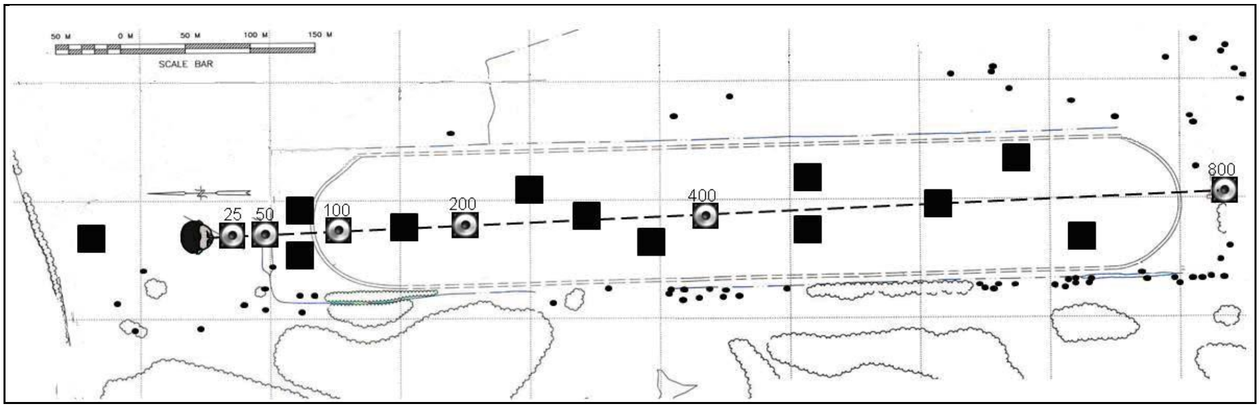

Figure 3. Outdoor test area on Spesutie Island where the study was conducted.

Note: The human head represents the listening station, squares with numbers next to them represent active loudspeakers and respective distances from the listener, and black squares without numbers represent dummy loudspeakers. Some elements of the figure are not to scale.

6.1.1 Instrumentation

The Spesutie Island study was conducted using a desktop PC, TDT System II Signal Processing System, Sony T77 DAT recorder, and supporting hardware and wiring. All equipment used by the listener and needed for monitoring acoustic conditions was located at the listening station shown in figure 4. Auxiliary equipment not used at the listening station was located in a trailer located at the north end of the range, 50 m to the left of the listening station (not shown in figure 2). Proprietary software was used to control the experiments, present sounds, and collect listener responses.

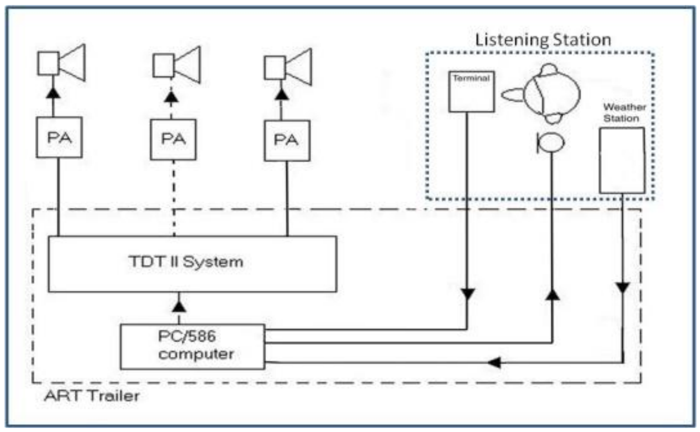

Figure 4. Block diagram of the instrumentation used in the study.

The listening station consisted of a table, chair, monitor, keyboard, and mouse. The station was situated on a concrete slab, protected from sun and bugs by a (2.1 m tall) canvas canopy with the walls made of bug netting. The station was also equipped with a Brüel and Kjaer 4133 microphone and a Davis Monitor II weather station. The microphone, mounted in an upright position 1 ft to the left of the listener, was used to record actual background noise and test signals during each sound presentation. A weather station, positioned 2 m to the left of the listener, was used to monitor temperature, humidity, wind strength, and wind direction. The data were automatically recorded in the listener file and were used to assess the effects of meteorological variables on sound propagation.

Eighteen boxes were scattered along the field within ±15° of the main listening axis of the listener (see figure 3). The boxes were made of wood with a removable front panel covered with acoustically transparent cloth. Six of the loudspeaker boxes housed test loudspeakers, and other boxes served as decoys. The boxes that contained the test loudspeakers were located 25, 50, 100, 200, 400, and 800 m away from the listening station (see figure 3). The loudspeakers were Electro-Voice Sx500+ stage monitors capable of delivering approximately 120-dB peak SPL at a 1-m distance from the loudspeaker. Loudspeakers were fed from Crown 2400 power amplifiers.

6.1.2 Listeners

Twenty-four listeners between the ages of 18 and 25 participated in the study (M = 21.4; SD = 3.6). The participants were recruited from the civilian population of Aberdeen Proving Ground and local colleges. All listeners had pure-tone hearing thresholds better than or equal to 20-dB hearing level (HL) at audiometric frequencies from 250 through 8000 Hz (ANSI S3.6-2010) and no history of otologic pathology. The pure-tone average threshold, calculated as the mean of hearing thresholds at 500, 1000, and 2000 Hz, was 1.2-dB HL for the entire group of listeners (48 ears) and varied from –5.0-dB HL to 8.3-dB HL for individual listeners. The difference between pure-tone thresholds in both ears was no greater than 10 dB at any test frequency. The listeners had no previous experience in participating in psychophysical studies. The average hearing threshold data for the entire group of participants are shown in figure 5.

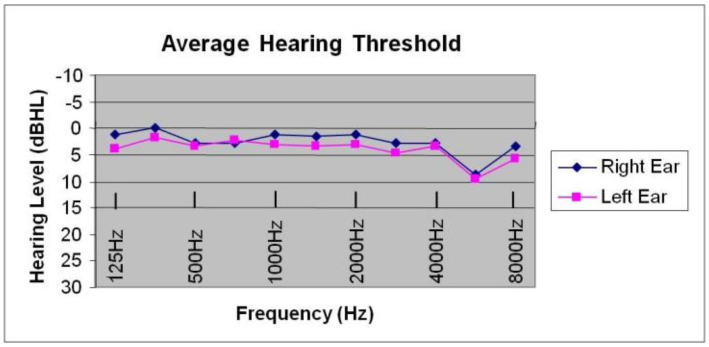

Figure 5. Average hearing threshold data for the group of 24 participants.

6.1.3 Sounds

Eight natural test sounds representing various sound sources were used in the study. Each sound had an overall duration of less than 1 s. All sounds were recorded by the authors, except the *Generator* and *Rifle* shot sounds, which were recorded during a different study. The recordings were made with an ACO 7012 microphone and a Sony T77 DAT tape recorder. The respective A-weighted sound pressure levels of the recorded sounds were measured during sound recording. These levels were recalculated for a 1-m distance from the sound source and are listed in table 3. The same sound levels measured at a 1-m distance in front of a loudspeaker were used in the study. The only exception was the *Rifle* sound, which had a sound pressure level that was too high at a 1-m distance (124 dB A) to be reproduced and was scaled down by 30 dB to 94 dB A. Spectral and temporal characteristics of all the sounds are shown in figure 6.

Table 3. List of test sounds and their production levels (in dB A) at 1-m distance from the sound source.

Test Sound	Sound Description	Sound Level
Boltclick	Rifle bolt closure sound	83
Dogbark	Dog bark	88
Generator	Generator sound	74
Joe	Male whisper (“Joe”)	72
Carhorn	Car horn sound	95
Rifle	Rifle shot sound	94
Throat	Throat clearing sound	74
Splash	Water splash sound	73

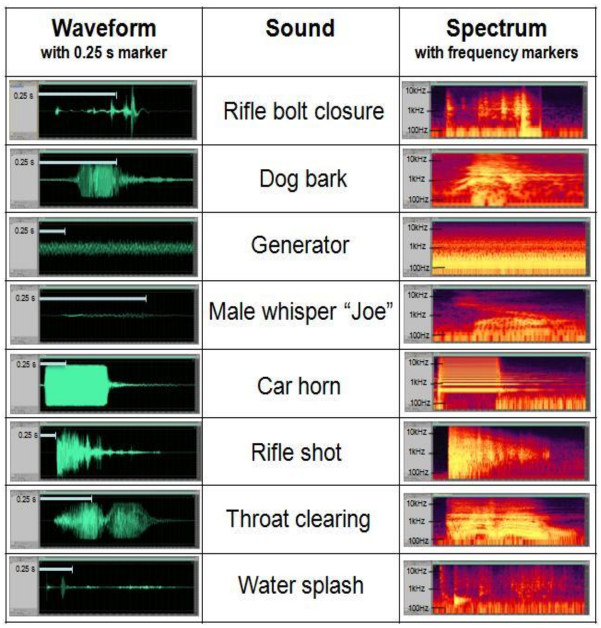

Figure 6. Temporal and spectral characteristics of the sounds used in the study.

6.1.4 Procedure

During the study the listener was seated at the listening station and was asked to listen to incoming sounds and respond using a computer keyboard and mouse. An individual test trial consisted of (1) a warning period indicating the beginning of a new test trial, (2) an observation period, and (3) a response period. A yellow-red-green status system light was built into the graphical user interface located on the monitor in front of the listener. The light was used to indicate the warning period (yellow light, 1 s), the observation period (red light, 10 s), and the response period (green light) when listeners recorded their responses. The length of the response period was not predetermined, and listeners could use this time to take short breaks. Listeners were also asked to wait prior to starting the next trial in the presence of occasional extraneous sounds, such as an airplane flying over or a car passing by, that could interfere with the performed task. To start the next trial, the listener used the mouse to select the “GO” button on the monitor and activate the yellow light that indicated the beginning of the new observation period.

During each observation period, a single test sound or no sound at all was presented. The sound lasted less than 1 s and could appear at any time during the observation period. The time when the sound appeared within the observation period was randomized. During the response period, the listener was asked (1) to indicate if a sound was present, (2) to identify the presented sound using a 12-item closed-set list of alternatives (which included all the sounds presented in table 3, plus bird, car engine, airplane, and other), and (3) to determine the distance to the sound source in either meters or yards. No response feedback was given to the listeners, but the listeners were told that some sounds may appear very often while others may appear occasionally or not at all.

Instructions regarding individual responses and the templates for response input were provided on the computer screen. Prior to the experiment, the specific sounds used in the study plus several others listed on the list of alternatives were demonstrated to the listener from a nearby loudspeaker, and a short training session was conducted.

One listening block included all seven sounds presented from all six loudspeakers with four repetitions each. In addition, 48 blank (no sound) trials were randomly presented in each block, resulting in 216 test trials per block. The responses made during the blank trials are not included in the presented data analysis. The order of sounds in each listening block was randomized. Four listening blocks were presented to each listener during a single listening session. The duration of the listening session depended on the duration of the rest periods taken by the listener but was typically 3.0 to 3.5 h. Large amounts of data were collected during the study, but in this report, we only discuss the auditory distance estimation data collected when the listener correctly recognized the sound. This restriction was made to minimize the effects of occasional environmental sounds (birds, cars, remote military sounds, airplanes, etc.) that could have been confused with the test stimuli on listeners’ responses.

6.1.5 Environmental Conditions

The study was conducted during a 2-week period in August. Historically, weather conditions in August in Aberdeen, MD, (Spesutie Island area; sea level altitude) are relatively stable with average relative humidity varying from a low value in the upper 50% range in the morning to a high value in the upper 80% range in the afternoon (mean value 71%). The average temperature during the day varies between 22 and 26 °C (mean value 24.1 °C). The wind conditions are characterized by the lowest average wind velocity throughout the year (about 5–6 km/h) (Anonymous, 2012a; 2012b). The Maryland Department of Natural Resources reports that there are over 400 species of birds and an untold number of insects inhabiting the area surrounding the test site (Anonymous, 2012c). Sounds made by many of these species created the ambient noise floor that served as a backdrop for our study. The time and temperature of the day also contributed to the acoustic behaviors of some of the wildlife. Many of the insects that contributed to our background sounds were crickets, katydids, cicada, bees, beetles, and grasshoppers. The average weather and noise conditions observed during the study are listed in table 4. The averages are mean values of the average conditions for individual listening sessions. The overall weather conditions were a bit warmer and drier than average for the area, resulting in an average heat index of 31 °C.

Table 4. Mean, median, and standard deviation values of the weather and noise conditions during data collection.

Parameter	Mean	Median	Standard Deviation	Unit
Temperature	28.5	29.0	2.3	°C
Relative humidity	67.6	68.0	0.2	%
Atmospheric pressure	1.005	1.006	0.018	Atm
Wind velocity	5.3	4.6	2.3	km/h
Wind direction	150.0	159.0	37.6	°
Noise level	50.7	53.0	5.2	dB

Stronger wind usually came from the south and southeast directions, while periods of weak wind came from the other directions. This behavior resulted in the relatively large standard deviation in wind direction parameter in table 4. The background noise at the listening station varied between 41 and 55 dB A-weighted depending on the time of the day and weather conditions, with many insects producing sounds in the range of 4–8 kHz. In general, the insects have unique comfort temperature zones in which they tend to make their calls. For example, for cicada *Tibicina*, the comfort temperature zone is 22–24 °C (Sueur and Sanborn, 2003). In addition, some insects (e.g., crickets) made calls with frequency of chirps directly related to the temperature (e.g., Toms, 1992). As the temperature becomes higher, the chirp rate also becomes higher.

6.2 Spesutie Island Study: Data

One of the main arbitrary decisions that had to be made was the decision about production levels of the loudspeaker-simulated sound sources used in the study. Since the goal of the study was to simulate natural sound sources as closely as possible and to learn some basics about the expected distance to an emitting sound source in an open space, all recorded sounds were reproduced at their natural recorded levels (except for the rifle shot). This means that each sound was produced at only a single level (see table 3) by all loudspeakers regardless of the distance of the loudspeaker from the listener. As a consequence, not all the sounds were heard and properly recognized by all listeners when emitted from distant loudspeakers. The variable audibility of sounds was also exuberated by changes in weather conditions across the study. This was the expected constraint of the implemented study design focused on natural production levels. The sound events and their levels were selected arbitrarily as well, but they were representative of specific sound sources. The selected experimental design focused on sound production level (as opposed to presentation level). Sound production level is considered important in studying how sound propagation in an open field affects perceived distance to a sound source.

The numbers of valid responses—that is, distance estimations made for correctly detected and recognized sound sources—made by the listeners for specific sound source–distance combinations are shown in table 5. The listeners made close to 100% valid distance estimations for distances up to 100 m and more than 50% valid estimations for distances up to 400 m for all the sounds except for *Joe* and *Throat*. They also made at least 50% valid estimations for *Carhorn* and *Rifle* sounds presented at an 800-m distance. The *Joe* and *Throat* sounds were practically inaudible to most listeners beyond a 100-m distance. Therefore, to avoid making conclusions on the basis of a very limited number of responses for some sound-distance combinations, only the combinations for which more than 50% of responses were collected were generally considered in data analysis. The few exceptions are noted in the text.

Table 5. Number of valid responses (detected and recognized sounds) made by the listeners.

Test Sound	**Distance (m)**					
	25	**50**	**100**	**200**	**400**	**800**
Boltclick						
Dogbark						
Generator						
Joe						
Carhorn						
Rifle						
Throat						
Splash						

Note: Black cells: 24–22 responses; gray cells: 18–12 responses; white cells: 10 or fewer responses.

To determine the significance of observed differences in the collected data, the data were subjected to a two-factor repeated measure ANOVA. The two factors were DISTANCE (five distances—the 800-m distance was not included because of the small number of data points) and SOUND (six sounds—*Joe* and *Throat* were not included because of the small number of data points). Both main factors, DISTANCE ($F_{4,8} = 4.39$; $p = 0.036$) and SOUND ($F_{5,10} = 3.93$; $p = 0.031$), as well as the interaction between these factors, were statistically significant ($F_{20,40} = 2.53$; $p = 0.006$). A post hoc Tukey HSD test for the DISTANCE factor showed no statistical difference in distance estimations for any two consecutive distances. However, larger differences between distances were significant. A relatively low-distance resolution in the reported data is to be expected because of the very large standard deviations of the listeners' responses. Observing the SOUND factor alone, we found that listeners responded in a relatively similar manner to all the sound sources simulated in the study. The only statistical difference in processing distances to different sound was between *Dogbark* and *Generator* ($p = 0.042$). This difference is discussed in the next section.

6.2.1 Effects of Distance

Distance was a main variable investigated in the study. To assess the general effect of distance on auditory distance estimations, estimates made by the listeners for all eight sounds were averaged together for each of the six distances. Two specific cases were considered: one, where only distance-sound combinations providing at least 50% of valid responses were considered, and two, where all the valid responses were averaged together regardless of the actual numbers of responses for specific sound-distance combinations. The mean and median results of both types of averaging are shown in figure 7. The standard deviations of the data are not shown since the data are characterized by high variability, and standard deviations are on the order of the range of the distance being estimated. Such large variability of the auditory estimation data is normal and is commonly reported (e.g., Laws, 1972; Mershon and King, 1975; Nielsen, 1993; Zahorik et al., 2005).

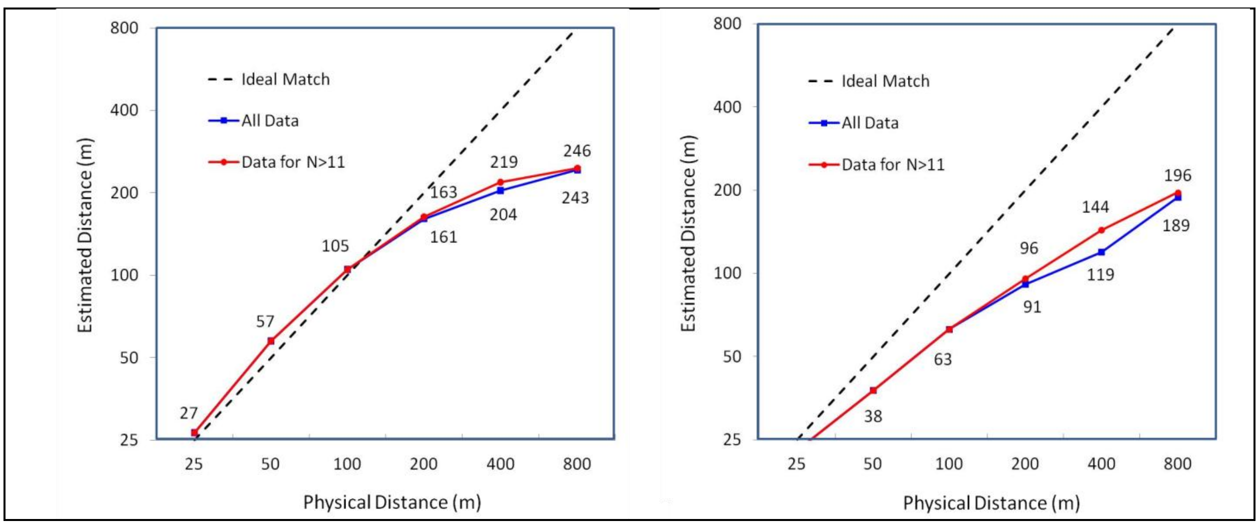

Figure 7. Auditory distance estimation for the six physical distances used in the study.

Note: Mean (left panel) and median (right panel) estimated distance as a function of physical distance for all collected data and for cases where the number of listeners making valid responses was larger or equal to 12.

The two curves shown in both panels of figure 7 are very close to each other despite the quite different number of listeners' responses for 200- to 800-m data. This supports the general validity of the data collected for sound-distance combinations resulting in 50% or more valid responses. The reported mean curves seem to reach their plateau of about 300 m at the distance of 1000–2000 m that can be hypothesized to be the *auditory horizon* (see Békésy, 1949; Bronkhorst and Houtgast, 1999) for the listeners in an open grassy field. The shape of the curves agrees with typical curves published in similar studies conducted at close distances and in enclosed environments. They can be approximated by power functions (see equation 1) $PD = 12d^{0.41}$ (data for $n \geq 12$; $R^2 > 0.9$) and $PD = 12d^{0.46}$ (all data; $R^2 > 0.9$). The power exponents of both functions are relatively close to the average values reported for shorter distances by Zahorik (2002a) and Zahorik et al. (2005).

The most notable property of the mean curves shown in figure 7 is that the listeners were either very accurate in their judgments or slightly overestimated the actual distance for distances up to 100 m. Recall that in almost all previous studies conducted in closed spaces, such accurate or overestimating judgments were typical for distances not exceeding 1–3 m (Bronkhorst and Houtgast, 1999; Brungart and Scott, 2001; Kim, 2009; McMurtry and Mershon, 1985; Speigle and Loomis, 1993; the last study was conducted in an open space). Brungart (2000) investigated auditory distance estimates over headphones to talkers recorded in an open field at distances ranging from 0.25 to 64 m and reported underestimation of distances larger than 1 m. Visual estimates made in an open field at distances as short as 10 m are also underestimated by observers (e.g., Andre and Rogers, 2006; Strauss and Carnahan, 2009).

A completely different character of the collected data emerges from the analysis of median values (figure 7, right panel). All distances from 25 to 800 m have been heavily underestimated by most of the listeners. The observed difference between the mean and median data results from the large variability of the listener responses. The majority of the listeners underestimated all judged distances, but several cases of overestimation greatly affected the mean values. Inspection of the data indicated that some listeners had a tendency to overestimate the actual distance to the sound source regardless of the type of sound source. The latter agrees with Cochran et al. (1968), who presented listeners (n = 20) with both live and recorded speech stimuli in an outdoor environment at distances from 1 to 29 m. Listeners estimated the distances using magnitude estimation judgment relative to a standard distance and underestimated the longest distance by as much as 30% when the standard distance was close to the listener.

One possible explanation of this fact is that some listeners had a tendency to overestimate distances to sound sources across all distances, which may be a sensory influence caused by a large visible space and a large number of potential sound sources located at large distances. They could expect a greater number of sounds coming from farther distances and could react accordingly. Calcagno et al. (2012) studied auditory and audio-visual distance estimations made by the listeners in a closed space for distances from 1 to 6 m and reported that auditory judgments made by the listeners underestimated the distances, while additional visual cues led to more accurate judgments or even overestimation of the distance. They hypothesized that auditory distance estimation is affected by visual awareness of environment, which hypothesis seems to be supported by the estimates made by some of our listeners. This also seems to agree with reports about visual judgments in that observers underestimate visual distances to targets to a greater degree in a large open area than in closed spaces (e.g., Aznar-Casanova et al., 2006; Teghtsoonian and Teghtsoonian, 1969; 1970).

Another possible explanation can be the presence of the intermodal range effect (Baird, 1997; Kowal, 1993). The range effect is the dependence of perceived difference between two stimulus values on the total range of available values.* For example, people may perceive the same distance as small or large depending on the extreme distance value available (imagined) as a valid response. The difference in distance of, say, 10 m may seem large in a small enclosed space but small in an open field. In addition, judgment of any stimuli along this range is a function of their relative location within the range (Ostrom and Upshaw 1968; Parducci, 1968). Some authors suggested that some people have a fixed response range (pattern), and this range is mapped into the actual stimulus range associated with a given attribute (Poulton, 1968; Teghtsoonian, 1971). Thus it may be hypothesized that distance over- and underestimation is a relative property of the perceived (imagined) maximum distance. For example, people may have a tendency to overestimate a distance if it is shorter than a certain fraction of a maximally perceived distance and underestimate it if it is longer than that.

6.2.2 Effects of Sound Type

The distance estimation functions for the individual simulated sound sources used in the study are shown in figure 8. The figure shows that distances to some of the sound sources (*Splash*, *Generator*) were underestimated regardless of the actual distance. This can be seen in both mean (left panel) and median (right panel) data representations. In contrast, the distances to sound sources producing relatively low output (*Joe*, *Throat*) that could only be heard at short distances were judged accurately (medians) or overestimated by some listeners more than the distances to other sound sources (means). These differences among sound sources may be due to the spectro-temporal properties of emitted sounds, listeners' expectations, or—in the latter case—to a relatively narrow range of effective distances that could be used for making estimates.

Interestingly, both *Joe* and *Throat* differed very much in both temporal and spectral properties (see figure 6). Considering this, it seems unlikely that their spectro-temporal properties and weather conditions could be the only or the main factors causing observed mean overestimation of distances to both sound sources. In addition, both are vocal sounds familiar to general listeners and should result in fairly accurate judgments. However, because of the requirements of the experimental design of the study, both sounds were relatively loud for their classes of sounds and whispered *Joe* was a voiced whisper. Therefore, it is possible that some listeners facing a large open space and hearing some louder-than-expected familiar sounds overestimated the actual distances trying "to use" the whole available space. This hypothesis could be verified in the

*Many psychophysical studies have shown that the stimulus range affects the exponent of the Power law equation (see equation 1). The exponent decreases approximately in proportion to a logarithmic increase in the range of the stimuli (Teghtsoonian, 1978; Poulton, 1989). While this is not a prevailing view, some researchers have argued (e.g., Poulton, 1989) that Power law's exponent has little to do with the sensory attribute but is "inversely related to the dynamic stimulus range over which the sensory system can process the attribute" (Baird, 1997, p. 85). Therefore, sensory "attributes with large dynamic ranges (such as loudness and brightness) have the lowest exponents, whereas attributes with short dynamic range (such as electric shock and lifted weight) have the highest ones" (Baird, 1997, p. 86).

future by conducting a similar study with both sounds presented with different intensities for blindfolded listeners. It may be expected that lack of a visual cue in a form of a large open space could lead to more accurate judgments of both sounds by all the listeners.

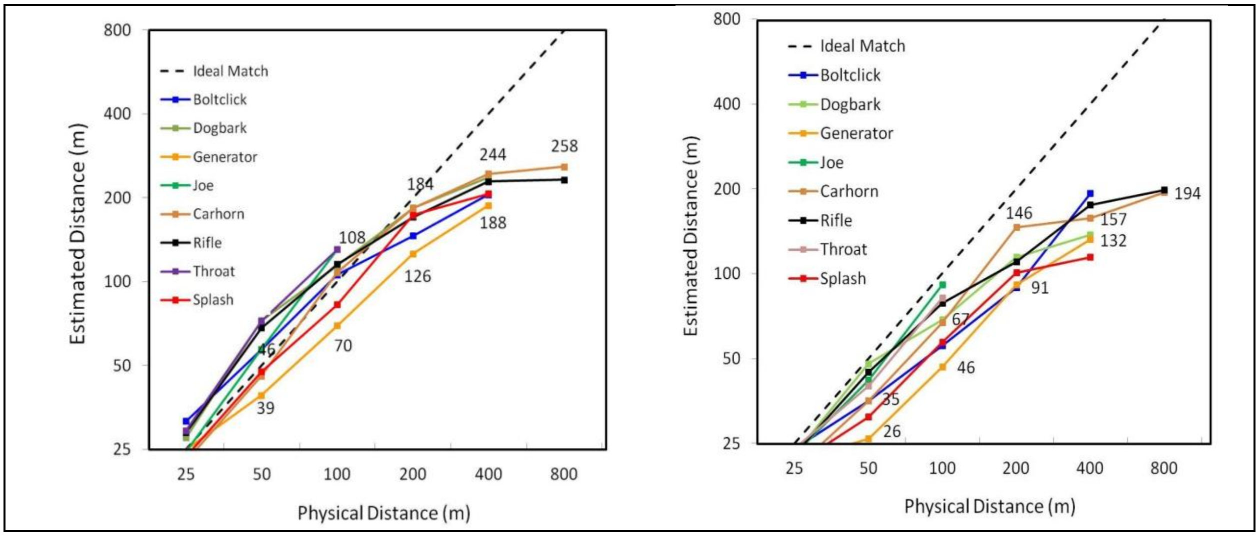

Figure 8. Auditory distance estimation for *Carhorn* (top numbers) and *Generator* (bottom numbers).

Note: Mean (left panel) and median (right panel) estimated distance as a function of physical distance for individual sounds and distances where the number of listeners making valid responses was larger than or equal to 12.

The data collected for *Boltclick*, *Dogbark*, *Rifle*, and *Carhorn* sounds show similar tendency and they mostly influenced the average data discussed in section 6.2.1. Surprisingly, scaling down the rifle sound by 30 dB was not reflected in any global shift of distance estimates made by the listeners. This may be because the actual distance to the "real" rifle location was much beyond the auditory horizon of the listeners. It may also be considered as a finding supporting the theory that the size of visible environment affects (limits, in this case) the range of available distance estimation options (alternatives).

The overall greater underestimation of distances to the *Splash* and *Generator* sounds was most likely due to expectations and previous life experience of the listeners. The *Generator* sound was originally produced by a 30-kW field generator that could be confused with residential outdoor power equipment, such as a lawn mower, which produces spectrally very similar noise but is typically heard from closer distances. The *Splash* sound had intensity and character typical for this class of sounds, but such sounds are seldom heard without close visual effect of splash. A mental image of a visually close event could potentially affect listeners' distance judgments.

Comparing the mean and standard deviations of the actual distances to the same of perceived distances has not revealed any special listeners' preference for a distance to the specific sound source. However, while participants generally underestimated the distance to all sound sources, the *Rifle* sound was less underestimated than expected at short distances. This may be attributed to adjusting its sound level down by 30 dB. As a result, listeners who had some previous experience to weapon fire may have thought the sound was farther away than it was presented.

6.2.3 Effects of Temperature, Humidity, and Atmospheric Pressure

The two main weather parameters recorded in this study were temperature and relative humidity. Temperature is the measure of the average amount of kinetic energy in the body or environment expressed on a normalized scale. Relative humidity is the ratio of the amount of moisture in the air to the total amount of moisture that can be held at a given temperature—that is, the degree of saturation of air with moisture.

To assess the effects of temperature and humidity on auditory distance estimation, the data collected during the times of highest and lowest values of both parameters have been analyzed separately. The four extreme weather conditions have been labeled hot, cool, dry, and humid, and their temperature and humidity ranges are listed in table 6. They are the extreme conditions in relation to weather conditions experienced during the study. Temperature and humidity of air are interdependent variables, and they cannot be absolutely separated for analysis purposes.

Table 6. Extreme weather conditions (temperature and relative humidity) recorded during the study.

Type of Weather	Temperature Range (°C)	Relative Humidity Range (%)	Average Temperature (°C)	Average Relative Humidity (%)
Hot weather	29–34	55–75	31	64
Cool weather	24–27	65–88	25	78
Dry weather	24–33	50–62	28	61
Humid weather	24–27	77–98	26	80

We analyzed distance estimation data obtained under the weather conditions listed in table 6 by comparing data collected during pairs of each opposite conditions: hot (five listeners) and cool (five listeners) and dry (four listeners) and humid (four listeners).

Hot-Cool: The five listeners exposed to *hot weather* conditions performed on the same level as the rest of the listeners. However, the listeners exposed to the *cool weather* condition underestimated distances for all sound sources more than the rest of the listeners. The mean distance estimates of the *cool weather* group were frequently as much as half of the estimates of the rest of the group. The behaviors of both groups were very uniform across distances from 25 to 100 m, and the behaviors become somewhat random at larger distances where the numbers of responses became quite sparse (all listeners' responses have been included in calculations).

Dry-Humid: For distances from 25 to 100 m, both the *dry weather* and *humid weather* listeners' responses differed from the mean values for the whole group. The *dry weather* group provided slightly larger distance estimates, and the *humid weather* group considerably smaller distance estimates than the rest of the group. The behaviors of both groups were the same for all sound sources with one exception. The *dry weather* conditions did not affect the judgments for the

Dogbark sound. For distances above 100 m, the effect of *dry weather* condition seemed to disappear, and above 200 m the effect of the *humid weather* condition becomes less clear.

These observations need to be treated with caution since they are based on relatively small samples of both the listeners and weather conditions. Since the changes in weather conditions also affect insects' behavior, the weather-related changes in the distance estimates may be affected, and to some degree explained, by the simultaneous changes in the background noise level. These changes are discussed in section 6.2.5. In addition, the listeners exposed to the "extreme" weather conditions had their own expectations and experience that could be different from those of others and which also could affect their responses in a unique way.

No clear effect of atmospheric (barometric) pressure has been noted in the study. Atmospheric pressure observed during the study was quite high and relatively stable, averaging 1.005 atm and varying from 1.001 to 1.009 atm across all listening sessions. Such pressure is typical for very warm weather and was slightly higher than the historically average pressure for the month of August in MD. Thus, because of relatively stable pressure conditions during the study, no specific effects of atmospheric pressure on distance estimation data were observed.

6.2.4 Effects of Wind

Wind is one of the major factors affecting sound wave propagation in the environment. Wind effects are quite complex, fast changing (e.g., wind gusts), and confounded by other weather conditions, and as a result, it is hard to assess wind effects in studies like the current one. Therefore, it was important for the study that all data collection was limited to relatively stable and weak wind conditions. The average wind speed throughout the study was 5.3 km/h (median = 4.6 km/h), with an average direction of 150° (SSE direction). On the Beaufort wind force scale, most wind conditions recorded in the study ranged between 0 (calm less than 1 km/h) and 1 (light air, between 1 and 5.5 km/h). There were several (nine) sessions with stronger winds ranging from 5.8 to 9.8 km/h, but in all cases except one (side wind; no strong perceptual effects) they were cases of the wind blowing downward (i.e., with the direction of propagating sound). This simplified the analysis of wind effects, limiting it to a comparison between data collected during strong downwind condition (eight cases) and data collected during no-wind and low-strength-wind conditions (15 cases; 0 to 5.15 km/h; various wind directions). The results of this analysis are shown in figure 9. The numbers in the graph are the ratios of distance estimates for no-wind and downwind conditions.

Under both no-wind and downwind conditions, the listeners generally underestimated distances to all sound sources. The distance estimates made by the listeners making judgments under no wind condition (M = 3.9 km/h; SD = 1.0 km/h) were about twice as large as those made by the listeners exposed to strong downwind conditions (M = 8.2 km/h; SD = 1.2 km/h). The results were somewhat dependent on the type of sound, with *Rifle* (~2.4 ratio) and *Carhorn* (~1.7 ratio) sounds being affected the most and the least, respectively. Both sounds were the most intense sounds, but they greatly differed in spectro-temporal properties. The *Rifle* sound was shorter and had a lower high-frequency content than the *Carhorn* sound (see figure 6). Therefore, the downward wind enhanced audibility of the *Rifle* sound and helped to preserve its less intense high-frequency content. This enhancement did not improve as much the audible properties of the *Carhorn* sound, because the *Carhorn* sound had high-frequency components intense enough to be clearly audible even without the help of the downwind.

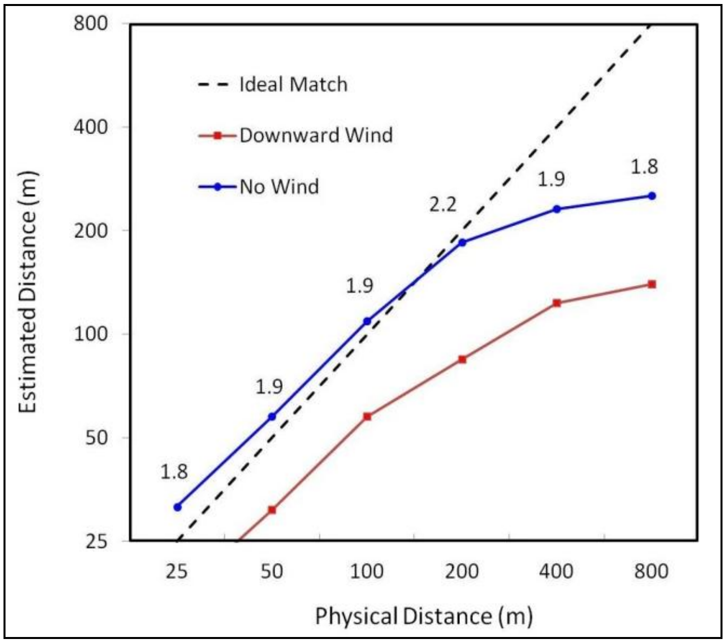

Figure 9. Comparison of auditory distance estimation data for no-wind and downwind conditions.

6.2.5 Effect of Background Noise

The background noise that affected the audibility of sounds produced by loudspeaker-simulated sound sources was for the most part the noise produced by ever-present insects. Occasional sounds produced by birds, animals, distant cars, and overflying airplanes were relatively rare, quite distinct, and usually quite short. They could affect one or two of the specific judgments, resulting usually in an invalid response, but they did not contribute significantly to the continuous noise present in the field. The average noise level across the study was about 51 dB A-weighted and was dependent on the weather conditions and time of the day. Typically, as the day became warmer, insect activity decreased, making the afternoons quieter than the mornings. As a result, most sounds were less audible during mornings than hotter afternoons. The relationship between the noise level and the temperature of air recorded throughout the study is shown in figure 10.

The spectral properties of the background noise are shown in figure 11. The insects' calls were most intense in the frequency band from about 4 to 8 kHz, and the number of calls in the frequency range from approximately 1.5 to 8 kHz greatly decreased with temperature.

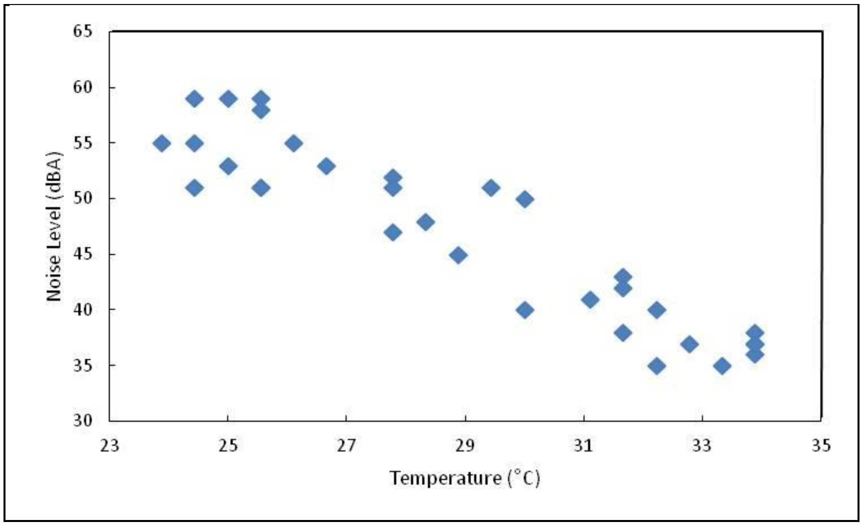

Figure 10. Relationship between background noise level (insects' calls) and temperature of air measured during the study. (Not all the points on the graph correspond to actual listening sessions.)

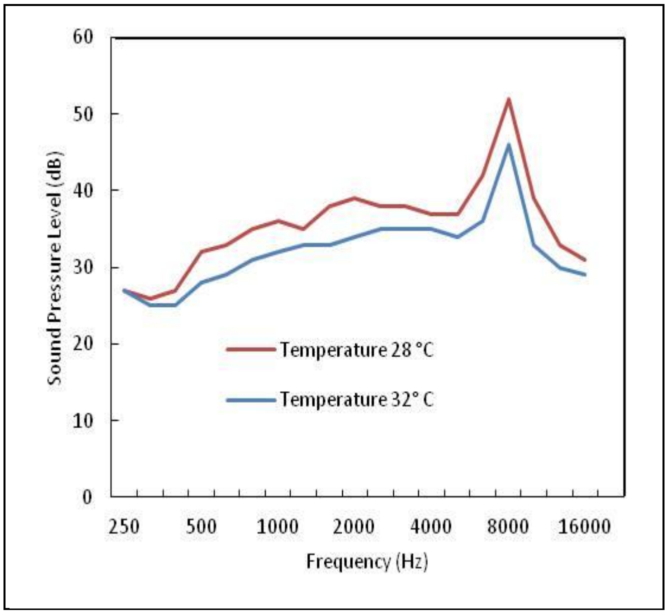

Figure 11. Examples of background noise levels in the morning (28 °C) and afternoon (32 °C) of the same day.

As discussed in section 6.2.3, cooler and more humid weather conditions generally resulted in greater underestimation of the distances to all sound sources. The participants that listened during these weather conditions usually gave smaller distance estimates despite the fact that the background noise level under these conditions was higher. Thus, two explanations for the observed effect are possible. First, that the effect of changes in air absorption had a stronger impact on the judgments of the listeners than simultaneous changes in noise level. Second, that poorer audibility due to high noise was associated with closer perceived distances to the sound sources.

If the overall sound level and high-frequency content of the sounds were less attenuated on the cooler, more humid days, then people may have felt the sound sources were closer because they heard them louder and clearer (due to the presence of high-frequency content) than on warm days, regardless of the noise level.

In addition, the greater the background noise level (lower SNR), the stronger the listener's impression was that the sound source was relatively near but was masked by a high level of background noise. This explanation seems to be supported by informal listeners' reports that at the higher the noise levels they "heard," the size of the space was smaller (reduced). Such reports about the noise effect also agree with the reports of research studies conducted in closed spaces according to which higher noise levels greatly masked environmental (reverberated) sounds, giving the impression that the space was smaller than its actual size.

Further, the observed effects might also be the result of the specific experience and predispositions of the small number of listeners who were exposed to the "extreme" listening conditions analyzed in our study. Further studies and analyses are needed to more completely explain these relationships and answer any related questions.

6.2.6 Individual Differences

Distance perception data obtained in the current study are marred by lack of consistency due to listeners' potential lack of ability to use distance estimation cues in open space and large individual differences among the listeners. Typical standard deviations of the group judgments were close to the size of the physical distance being estimated and quite independent of the type of sound source. The large individual differences and disparities in judgments have been also encountered in the closed spaces by other researchers. Recently, Wisniewski et al. (2012) used open field recordings reproduced in a closed space and reported substantial individual differences among the listeners in judging auditory distance. The distance judgment differences ranged from 51% to 77%. However, the listeners made the same general pattern of errors—a finding that is not supported by the results of the present study. Similar, widely varying results of distance estimation have been reported in visual distance estimation studies conducted in open fields. The results of these studies indicate that regardless of sensory input, we have not yet found a single relationship between physical and perceived space that is consistent with distance judgments in outdoor contexts (Norman et al., 2005; Jackson, 2009).

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